PNNL-29378

Washington Clean Energy Fund: Energy Storage System Consolidated Performance Test Results

February 2020

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Prepared for the U.S. Department of Energy under Contract DE-AC05-76RL01830

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Pacific Northwest National Laboratory
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Executive Summary

Integration of energy storage into the U.S. grid has been gathering momentum across the industry, especially as penetration of power generated by renewable resources increases. Several states have storage procurement targets to deal with a variety of issues, such as afternoon total system load ramping requirements, frequency regulation/control, and integration power generated from by renewable resources. This report presents the performance test results for battery energy storage systems (BESS) funded by the Washington Clean Energy Fund (CEF) 1 Program ($14.3 million in state funding supporting a total investment of $43 million). For each project, the technical attributes of the BESS were tested, defined, and evaluated in detail. These projects were funded jointly by Avista, the Snohomish Public Utility District (SnoPUD), Puget Sound Energy (PSE), the Washington CEF, and the U.S. Department of Energy Office of Electricity Delivery and Energy Reliability (DOE-OE).

Figure ES.1 presents an overview of the Washington CEF BESS characteristics at each site where the BESS technical performance was characterized using the DOE-OE Energy System Storage Performance Protocol.[1] After conducting baseline tests to evaluate the general characteristics of each BESS, its performance was measured under various energy storage use cases to evaluate key performance metrics relevant to real-world economic operation. Outcomes of these analyses will be beneficial both in understanding the performance of the BESS and in designing appropriate long-term operational strategies.

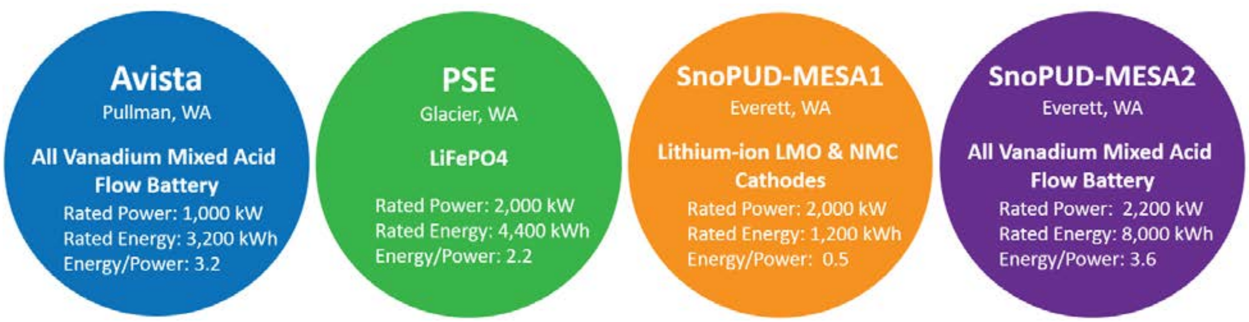

Figure ES.1. Washington CEF Battery System Characteristics

The CEF Grid Modernization Program supported evaluation of a range of use cases. The mapping of use cases performed by each respective project is shown in Figure ES.2. The duty cycles were designed to simulate real-world economic performance. Pacific Northwest National Laboratory (PNNL) used price and other system data to define duty cycles, specific to each BESS and each utility, for each use case. Results presented here reflect the performance monitored during the extensive testing program. It is important to note that while PNNL was able to obtain enough data to evaluate the performance of each CEF-funded BESS, both UniEnergy Technologies FBESSs tested under this program have since ceased operation.

[1] Viswanathan V, A. Crawford, P. Balducci, T. Hardy, J. Alam, and D Wu. 2017. *Washington Clean Energy Fund: Energy Storage System Performance Test Plans and Data Requirements*. PNNL-26492, Pacific Northwest National Laboratory, Richland, Washington.

	Avista All Vanadium Mixed Acid Flow Battery	PSE LiFePO4	SnoPUD MESA1 Lithium-Ion LMO & NMC Cathodes	SnoPUD MESA2 All Vanadium Mixed Acid Flow	Sno-Controls Integration Evaluation of real-time system operations
Use Case 1: Energy Shifting					
Energy shifting from peak to off-peak on a daily basis	●	●	●	●	
System capacity to meet adequacy requirements	●	●	●	●	
Use Case 2: Provide Grid Flexibility					
Regulation services	●	●		●*	
Load following services	●	●		●*	
Real-world flexibility operation	●	●		●*	
Use Case 3: Improving Distribution Systems Efficiency					
Volt/Var control with local and/or remote information	●		●	●	
Load-shaping service	●	●	●	●	
Deferment of distribution system upgrades	●	●			
Use Case 4: Outage Management of Critical Loads					
Outage management of critical loads		●			
Use Case 5: Enhanced Voltage Control					
Volt/Var control with local and/or remote information and during enhanced CVR events	●				
Use Case 6: Grid-connected and islanded micro-grid operations					
Black Start Operation	●				
Micro-grid operation while grid-connected	●				
Micro-grid operation while in islanded mode	●				
Use Case 7: Optimal Utilization of Energy Storage					
Optimal utilization of energy storage	●	●			●

*Use case relies on simulated signals because these services are not provided by SnoPUD.

Figure ES.2. CEF Project Use Cases

Because BESSs have quite diverse characteristics, it was important to first characterize performance over time using a DOE-OE standardized baseline test procedure for energy storage. This standardized baseline test includes representative generic duty cycle profiles, test procedure guidance, and calculation guidance for determining key BESS characteristics, including energy capacity, response time, internal resistance, and efficiency. After conducting baseline tests to evaluate the general characteristics of the BESS, tests of the parameters identified for the various use cases listed in Figure ES.2 were performed and measurements were taken to evaluate key BESS performance metrics. Outcomes of these analyses will help the participating utilities and the wider industry understand the performance of BESSs during field operations, which will inform design of appropriate long-term operational strategies.

Summary of Work Performed

This report summarizes the technical performances of the four battery systems based on several reference performance tests and use case tests. The following performance metrics were identified for comparison across battery technologies, with the results shown in Figure ES.3:

- Normalized discharge energy
- Round trip efficiency (RTE) with and without auxiliary consumption
- Maximum normalized pulse power for charge and discharge
- Normalized (with respect to rated power) ramp rate
- Response time(s)
- Normalized (with respect to rated power) root mean square error
- MW-normalized internal resistance

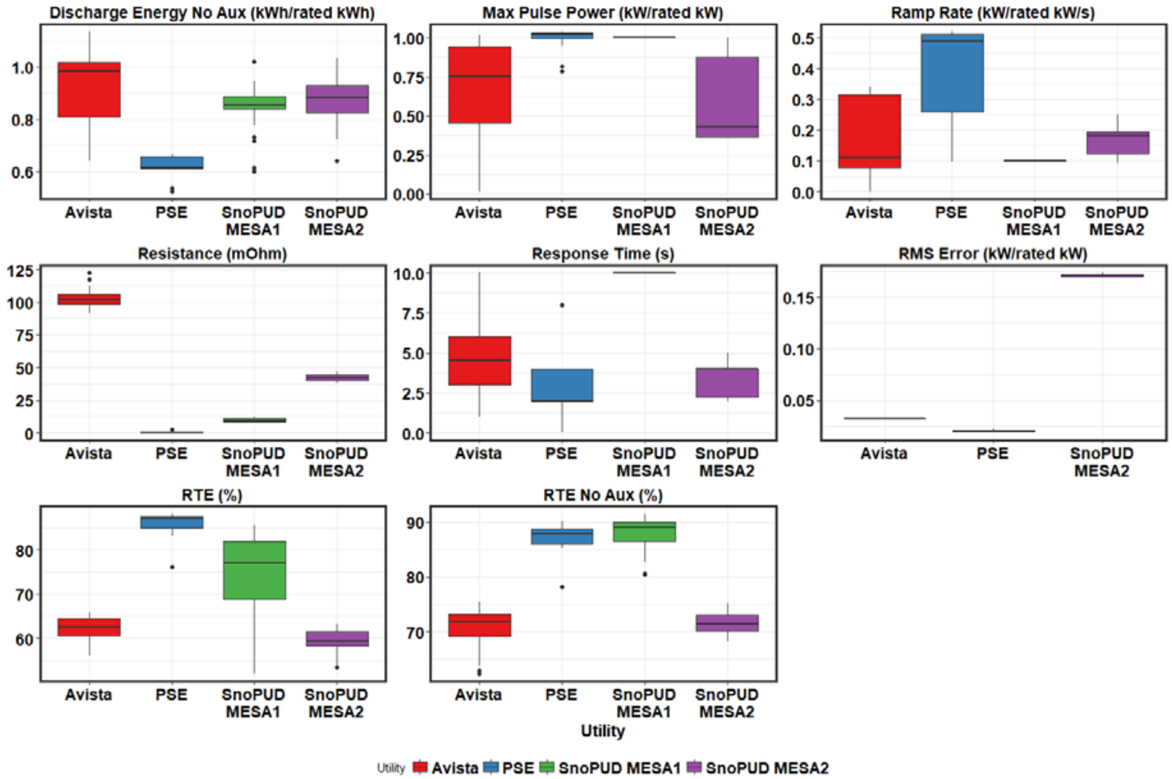

Figure ES.3. Performance of BESS for All Utilities

Key Questions and Outcomes

1. **What is the range of normalized energy during the reference performance capacity tests for all technologies?**

   The depth of discharge for the Li-ion BESSs was restricted to 72 to 85%. This restricted the delivered energy to 63 to 85% of rated energy. Because no such restrictions were applied to the flow battery energy storage systems (FBESS), the maximum discharge energy for FBESSs exceeded the rated energy. However, the FBESSs delivered energy that decreased linearly with increasing discharge rate.

2. **What is the RTE for each technology at rated power?**

   The RTE for the PSE Li-ion BESS at 86% was much higher than the Modular Energy Storage Architecture 1 (MESA1) Li-ion BESS at 75%. The reason was the higher auxiliary consumption of the latter associated with its high power-to-energy (P/E) ratio. The RTE of MESA1 BESS was marginally higher at 88% once auxiliary consumption was ignored. The RTE for the FBESSs was in the 55 to 60% range, peaking at 50% of rated power.

3. **How important is auxiliary consumption?**

   The RTE for the high P/E MESA1 BESS dropped at 12% of rated power because of a high contribution from auxiliary consumption. The high energy-to-power ratio PSE BESS was not tested below 37% rated power; hence, this RTE drop at low power was not observed. Excluding auxiliary consumption, the RTE at low power was not much lower than peak RTE for MESA1. The peak in RTE was probably due to the sweet spot corresponding to higher operating temperature. For the FBESSs, the RTE increased linearly with decreasing power when auxiliary consumption was excluded in the power range investigated.

4. **How does state-of-charge (SOC) range of operation affect RTE?**

   For the Li-ion BESSs, RTE was not significantly affected by SOC range. For the FBESSs, since open circuit voltage decreases linearly with decreasing SOC, the RTE decreases as average SOC decreases. This was observed in use cases such as arbitrage and capacity.

5. **How was BESS performance affected by operating conditions?**

   The RTE was highly dependent on average power, SOC range, and rest duration. While reference performance tests were done across a wide SOC range, use case testing, such as arbitrage, subjected the BESS to different SOC ranges. Therefore, a battery model was developed to predict performance across a wide operating range to optimize battery duty profile. For example, long rest periods and low operating power is very detrimental to RTE. Frequency regulation, which typically has a low average power, registered a low RTE.

6. **Can the battery technologies attain rated power across the entire SOC range?**

   Li-ion BESSs attained rated power during charge and discharge across the SOC range tested, while FBESS could not attain rated charge power at >50% SOC.

7. **What is the response time to maximum power for each technology?**

   The response time was 2.5 to 5 seconds for all technologies. The ramp rate, based on limited analysis for Li-BESS, was a mirror image of the resistance, increasing when the resistance decreased and vice versa, while the response time increased with increasing resistance.

8. **What unique thermal management issues were identified**

   FBESSs are endothermic during charge, while Li-ion BESSs are net exothermic during charge and discharge. Since the FBESS did not have active heating, this necessitated multiple charge and discharges during start-up in winter to get the battery heated up. However, if heating is also present, this disadvantage turns into a net benefit—the battery serves as a thermal management system due to cooling during charge followed by heating during discharge.

   For comparison across the same technology, the product of P/E and MW-normalized resistance was used as a proxy for rate of rise of temperature per unit power. For comparison across technologies, the ratio of MW-normalized resistance to system mass per unit power was used as a proxy for rate of rise of temperature per unit power. On both accounts, the MESA 1 BESS had the highest numbers, in line with its highest rate of rise of temperature per unit power. Considering it is a high-power BESS, the battery choice does not appear to be in line with its end use.

9. **What was the system availability?**

   FBESSs were available 50 to 55% of test days, while Li-ion BESS availability was in the 62 to 75% range. Direct current battery issues dominated FBESS unavailability, while direct current battery and site-related issues dominated Li-ion BESS unavailability.

10. **Was degradation observed for any technology?**

    No, the test duration was not long enough to observe meaningful degradation.

11. What was the overarching site controller issue that needed to be addressed?

Commands to the FBESS are sent at the inverter level, while BESS response is tracked at the grid level. This leads to the FBESSs providing less power than requested during discharge and absorbing more power during charge to power auxiliary loads. System tracking at the grid level for volatile signals is poor for the same reason.

Communication-related delays need to be accounted for, especially for use cases such as frequency response and frequency regulation, where response time of the FBESS is important. For example, the PSE site had an ~5-second communication delay that was accounted for in signal processing.

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We are grateful to Mr. Bob Kirchmeier, Senior Energy Policy Specialist at the Washington Department of Commerce, for providing Clean Energy Fund program leadership and support to Pacific Northwest National Laboratory (PNNL) and our utility partners. We are also grateful to Dr. Imre Gyuk, the Energy Storage Program Manager in the Office of Electricity at the U.S. Department of Energy, for providing financial support and leadership on this and other related work at PNNL. We wish to acknowledge Philip Craig from BlackByte Cyber Security; the team members from Avista, including Matt Michael, Robert Cloward, James Gall, Reuben Arts, John Gibson, Curt Kirkeby, and Kenny Dillon; Uni Energy Technologies team members Chauncey Sun, Brad Kell, and David Ridley; the team members from the Snohomish Public Utility District, including Bob Anderson, Arturas Floria, Kevin Lavering, Nick Peretti, Mike Shapley, Kelly Wallace, and Jason Zyskowski; and the team members from Puget Sound Energy, including Kelly Kozdras and Shane Richards.

Acronyms and Abbreviations

BESS	battery energy storage system(s)
BMS	battery management system
BPA	Bonneville Power Administration
CEF	Clean Energy Fund
DC	direct current
DOD	depth of discharge
DOE-OE	U.S. Department of Energy Office of Electricity Delivery and Energy Reliability
E/P	energy-to-power ratio
FBESS	flow battery energy storage system
kW	kilowatts
kWh	kilowatt-hours
MESA	Modular Energy Storage Architecture
MW	megawatt(s)
MWh	megawatt hour(s)
OCV	open circuit voltage
PCS	power conversion system
P/E	power-to-energy ratio
PNNL	Pacific Northwest National Laboratory
PSE	Puget Sound Energy
RMSE	root mean square error
RPT	reference performance test
RTE	round trip efficiency
SnoPUD	Snohomish Public Utility District
SOC	state of charge

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1.0 Introduction

Energy storage integration into the U.S. grid has been gathering momentum across the industry, especially as renewable generation penetration increases. Several states have storage procurement targets to deal with a variety of issues such as afternoon total system load, ramping requirements, frequency regulation/control, and integration of renewable energy. This report presents the performance test results for battery energy storage systems (BESS) funded by the Washington Clean Energy Fund (CEF) 1 Program. CEF 1 provided $14.3 million in state funding, supporting a total investment of $43 million for the purchase and deployment of grid-scale BESSs at three utilities in Washington State—Avista, Puget Sound Energy (PSE), and Snohomish Public Utility District (SnoPUD).

Table 1.1 presents an overview of the Washington CEF BESS characteristics. At each site, BESS technical performance has been characterized using the U.S. Department of Energy Office of Electricity Delivery and Energy Reliability (DOE-OE) Energy System Storage Performance Protocol (Viswanathan et al. 2014). The DOE-OE Protocol includes representative generic charge/discharge storage duty cycle profiles, test procedure guidance, and calculation guidance for determining key BESS characteristics, including energy capacity, response time, internal resistance, and round trip efficiency (RTE).[2] After conducting baseline tests to evaluate the general characteristics of each BESS, performance was measured under various energy storage use cases to evaluate key performance metrics relevant to real-world economic operation. Outcomes of these analyses will be beneficial in understanding the performance of the BESS, and when designing appropriate long-term operational strategies.

Table 1.1. Washington CEF Battery System Characteristics

Utility	Site	Chemistry	Rated Power (kW)	Rated Energy (kWh)	Energy-to-Power Ratio (E/P) (h)
Avista	Pullman	All Vanadium Mixed Acid Flow	1,000	3,200	3.2
PSE	Glacier	LiFePO4	2,000	4,400	2.2
SnoPUD	Everett MESA1	Lithium-ion $LiMn_2O_4$ and nickel-manganese-cobalt oxide cathodes	2,000	1,000	0.5
SnoPUD	Everett MESA2	All Vanadium Mixed Acid Flow	2,200	8,000	3.6

MESA = Modular Energy Storage Architecture

The four BESSs defined in Table 1.1 range from 1 to 8 megawatt-hours (MWh) of rated energy and include three different battery technologies—two types of Li-ion battery systems and one type of flow battery energy storage system (FBESS). UniEnergy Technologies provided two vanadium-flow battery systems, one at the Avista Pullman Site and the Modular Energy Storage Architecture (MESA) 2 BESS at a SnoPUD substation in Everett, Washington, Washington. PSE deployed a 2-megawatt (MW), 4.4-MWh rated BESS consisting of lithium iron phosphate ($LiFePO_4$)-graphite cells at Glacier, Washington. MESA1 consisted of two different Li-ion battery subsystems, one using spinel $LiMn_2O_4$ cathodes and the other using a layered nickel-manganese-cobalt oxide cathode.

[2] The RTE is the ratio of discharge energy to charge energy.

Reference tests were performed on all four systems and are described in the DOE-OE Test Protocol (Viswanathan et al. 2014). Using these reference performance tests (RPT), several fundamental BESS performance metrics, including RTE, response time, ramp rate, internal resistance, and reference signal tracking were determined for all four BESSs. These findings have been published in separate test reports for each project. This document consolidates the findings across the various projects and their various chemistries.

The RPT consisted of capacity, generic frequency regulation duty cycle, and pulse tests to determine response time, ramp rate, and internal resistance. For capacity tests, the power levels correspond to various fractions of rated power and various multiples of rated energy (or C rates). When direct comparison is not practical or appropriate, this report describes the limitation. For example, for an FBESS, the RTE depends on the fraction of rated power used since the energy content can be varied independently. Hence, representing the results in C rates may be misleading when the energy of the battery is changed while keeping the rated power unchanged.

The CEF Grid Modernization Program supported the evaluation of a range of use cases. The mapping of use cases performed for each respective project is shown in Table 1.2. The duty cycles presented in Table 1.2 were designed to simulate real-world economic performance. Pacific Northwest National Laboratory (PNNL) used price and other system data to define duty cycles, specific to each BESS and each utility, for each of these use cases. Those duty cycles are defined in Viswanathan et al. 2017.

Table 1.2. CEF Project Use Cases

Use Case and Application	Avista	PSE	Sno-MESA 1	Sno-MESA 2	Sno-Controls Integration
UC1: Energy Shifting					
Energy shifting from peak to off-peak on a daily basis	X	X	X	X	
System capacity to meet adequacy requirements	X	X	X	X	
UC2: Grid Flexibility					
Regulation services	X	X		X*	
Load following services	X	X		X*	
Real-world flexibility operation	X	X		X*	
UC3: Improving Distribution Systems Efficiency					
Volt/Var control with local and/or remote information	X		X	X	
Load-shaping service	X	X	X	X	
Deferment of distribution system upgrade	X	X			
UC4: Outage Management of Critical Loads					
Outage management of critical loads		X			
UC5: Enhanced Voltage Control					
Volt/Var control with local and/or remote information and during enhanced conservation voltage reduction events	X				
UC6: Grid-connected and islanded micro-grid operations					
Black Start Operation	X				
Micro-grid operation while grid-connected	X				
Micro-grid operation while in islanded mode	X				
UC7: Optimal Utilization of Energy Storage					
Optimal utilization of energy storage	X	X			X

Note: Use case relies on simulated signals because these services are not provided by SnoPUD.

2.0 Reference Performance Capacity Tests

For all utilities, baseline capacity tests were performed to gauge BESS performance. Note that for Avista and SnoPUD MESA2, the discharge power varied while the charge power was kept constant. This was because the vendor-recommended continuous charge power was 600 kilowatts (kW) for Avista and 1,200 kW for MESA2, with lower charge power at starting temperatures less than a threshold. For MESA2, additional tests were done to determine the effect of charge rate using a nominal discharge rate of 1,100 kW and maximum charge rate of 1,600 kW. For the Li-ion BESSs at SnoPUD MESA1 and PSE, the capacity tests were performed with equal charge power and discharge power for various power levels.

Table 2.1 shows the summary of power flow meter data available for each project. For projects where the requested power tag was present, the communication lag and hardware response time could be determined; however, for MESA1, where this tag was not present, the response time includes both a communication lag and hardware response time.

Table 2.1. Summary of Power Flow Tag Availability

	Avista	PSE	SnoPUD MESA1	SnoPUD MESA2
Power at Grid	X			X
Power at Battery	X	X	X	X
Aux Power		X	X	
Requested Power	X	X		X

For Avista, capacity tests were performed before and after one cycle of use case tests, and for PSE and MESA1, two cycles of use case testing were performed; thus, three sets of capacity tests were performed over the course of testing. For MESA2, cycle 1 of use case testing could not be completed due to issues with BESS string failures. This resulted in only one set of RPTs. Different rest periods for each half cycle were used at each site—15 minutes at Avista and MESA2, 30 minutes at PSE, and 1 hour at MESA1. Hence, the RTE without rest, along with RTE without auxiliary consumption, allows for comparison on a uniform basis. The results of these tests are given in Table 2.2 to Table 2.4. While the state-of-charge (SOC) range for MESA1 as reported in Table 2.2 to Table 2.4 exceeds the 7.5 to 92.5% SOC range, this is due to a quirk in the SOC behavior during rest after charge or discharge. Table 2.5 summarizes the discharge energy as a fraction of rated energy at various C rates.

Table 2.2. High Rate Capacity Test Comparison

Parameter	Avista	PSE	SnoPUD MESA1	SnoPUD MESA2
Discharge Power (kW/Rated kW)	1.00	1.00	0.97	0.75
Charge Power (kW/Rated kW)	0.60	1.01	1.03	0.55
Min SOC	50	10	6	48
Max SOC	99	82	88	97
Charge Energy (kWh/rated kWh)	1.11	0.76	1.15	0.88
Discharge Energy (kWh/rated kWh)	0.63	0.65	0.87	0.52
Charge Energy No Aux (kWh/rated kWh)	1.04	0.75	1.00	0.55
Discharge Energy No Aux (kWh/rated kWh)	0.66	0.66	0.89	0.80
RTE (%)	57	86	77	59
RTE No Rest (%)	57	87	86	60
RTE No Aux (%)	63	88	89	68

Table 2.3. Mid-Rate Capacity Test Comparison

Parameter	Avista	PSE	SnoPUD MESA1	SnoPUD MESA2
Discharge Power (kW/Rated kW)	0.52	0.53	0.50	0.52
Charge Power (kW/Rated kW)	0.60	0.55	0.52	0.49
Min SOC	32	10	7	40
Max SOC	99	82	98	95
Charge Energy (kWh/rated kWh)	1.48	0.77	1.12	0.97
Discharge Energy (kWh/rated kWh)	0.95	0.66	0.92	0.58
Charge Energy No Aux (kWh/rated kWh)	1.38	0.76	1.04	0.61
Discharge Energy No Aux (kWh/rated kWh)	1.01	0.66	0.94	0.86
RTE (%)	64	83	83	60
RTE No Rest (%)	64	83	87	61
RTE No Aux (%)	73	85	90	71

Table 2.4. Low Rate Capacity Test Comparison

Parameter	Avista	PSE	SnoPUD MESA1	SnoPUD MESA2
Discharge Power (kW/Rated kW)	0.40	0.36	0.13	0.25
Charge Power (kW/Rated kW)	0.60	0.37	0.18	0.55
Min SOC	30	10	7	29
Max SOC	100	82	96	97
Charge Energy (kWh/rated kWh)	1.57	0.77	1.12	1.14
Discharge Energy (kWh/rated kWh)	1	0.65	0.77	0.65
Charge Energy No Aux (kWh/rated kWh)	1.44	0.76	1.00	0.76
Discharge Energy No Aux (kWh/rated kWh)	1.07	0.66	0.82	1.01
RTE (%)	64	88	69	58
RTE No Rest (%)	64	88	73	58
RTE No Aux (%)	74	90	82	75

Table 2.5. Comparison of Discharge Energy in kWh/rated kWh at Various C Rates

Discharge Rate	Avista Baseline	Avista Post Cycle 1	Avista Post Cycle 2	PSE Baseline	PSE Post Cycle 1	PSE Post Cycle 2	SnoPUD MESA1 Baseline	SnoPUD MESA1 Post Cycle 1	SnoPUD MESA1 Post Cycle 2	SnoPUD MESA2 Baseline
1C	-	-	-	-	-	-	0.90	0.92	0.89	-
2C	-	-	-	-	-	-	0.85	0.87	0.86	-
C/2	-	-	-	-	-	-	0.84	0.88	0.89	-
C/2.2	-	-	-	0.66	0.61	0.52				-
C/3	-	0.62	0.66	-	-	-	0.85	0.84	0.82	-
C/4	0.81	0.86	0.81	0.66	0.62	0.54				-
C/5	-	-	-	-	-	-				0.80
C/6	1.02	1.00	1.01	0.66	0.61	0.62				-
C/7										0.88
C/8	1.08		1.14							
C/9										
C/15										1.01

The delivered energy ranged from 0.5 times rated energy to 1.1 times rated energy, while the RTE ranged from 57 to 90% depending on BESS technology, operating parameters, and whether the auxiliary load's energy consumption is accounted for in the test. The RTEs for the FBESSs at Avista and MESA2 are similar, while the RTEs for the Li-ion BESSs at PSE and MESA1 are similar across the various rates. The RTE increase when auxiliary consumption was excluded was higher for FBESSs since pump-related loads contributed to higher auxiliary consumption normalized on the basis of rated power.

The SOC range for Li-ion BESSs was limited to less than 100%, while there were no such limits placed on the FBESSs. The MESA1 BESS SOC range was limited to 7.5 to 92.5% by the vendor. To avoid string imbalance related issues, the PSE BESS SOC was limited to 82% on the high side. On the low side, due to an error in reported SOC versus actual SOC, the analysis was done with the lower SOC limit set to 10%.

For the high rate case, the RTE of the FBESSs when rest was excluded was 57 to 60%, while for the Li-ion BESSs it was 86 to 87%. When auxiliary power consumption is excluded, the RTE of the FBESSs increased to 63 to 68%, and the RTE of the Li-ion BESSs increased slightly to the 87 to 89% range. Due to a lower SOC range of operation (or depth of discharge [DOD]) and lower measured maximum discharge energy compared to rated energy, PSE discharge energy was only 65% of its rated energy, while MESA1 delivered energy was 0.89 times its rated energy. While the DOD was the same for the Avista and MESA2 FBESSs at 49%, the delivered energy for Avista was 63% of its rated energy compared to 52% for MESA2. The following two things stand out:

- The delivered discharge energy for Li-ion BESSs is in line with the SOC change, while for FBESSs, the delivered energy at 49% DOD is much higher in terms of percent of rated energy. This is because the open circuit voltage (OCV) for FBESSs decreases linearly with decreasing SOC, resulting in a greater amount of energy per unit change in SOC in the high SOC region while Li-ion BESSs voltage profile is much flatter and hence has more consistent energy per unit SOC across the SOC range.
- The delivered energy for MESA2 at 52% of rated energy is much lower than that for Avista FBESS, due to an imbalance of stack modules within each string.

MESA1 performed the best at “moderate rate,” which was 0.5 times rated power, delivering 92% of rated energy at an RTE of 87% when rest is excluded. Delivered energy for PSE was stable across the power levels at 0.66 times rated energy. This high RTE area for the MESA1 BESS corresponded to an operation regime where the BESS temperature (T) improved performance; at lower rates, lower temperature resulted in lower direct current (DC) DC-DC efficiency, while at higher rates, the higher temperatures were not sufficient to counter electrochemical losses and higher auxiliary consumption. The RTE curve flattened out when auxiliary consumption was excluded, but still maintained a peak at 0.5 times rated power.

The Avista FBESS delivered 95% of its rated energy at 52% of rated power, while the MESA2 battery absorbed and delivered lower energy compared to the Avista FBESS due to string imbalance issues. Note that the RTE for MESA2 was in line with the RTE for Avista, at 61 and 64%, respectively, increasing to 71 to 73% when auxiliary consumption is excluded. This indicates that higher internal resistance or electrolyte crossover were not factors in its lower performance.

The PSE delivered energy, as stated earlier, was unchanged at 0.36 times rated power, while the MESA1 BESS, due to higher auxiliary consumption, delivered much lower energy at 0.77 times rated energy at 0.13 times rated power. At a lower rate of 0.4 times rated power, the Avista BESS delivered its rated energy, while MESA2 delivered only 65% of its rated energy at 0.25 times rated power due to string imbalance. The MESA2 FBESS was discharged in the range of 0.25 to 0.75 times rated power, while the Avista FBESS discharge power ranged from 0.4 to 1 times rated power. Although the Avista FBESS efficiency was higher, the trends were similar. Both FBESS RTEs peaked at 0.52 times rated power, while the RTE increased with decreasing discharge power in the range investigated. The lower RTE for the MESA2 FBESS can be attributed to string imbalance, which stops the discharge prematurely when the weak string drops out.

Figure 2.1 and Figure 2.2 show the normalized discharge energy capacity for the BESSs at various discharge rates. The data is presented as discharge as a fraction of rated power in Figure 2.1 and as C rates (multiples of rated energy) in Figure 2.2. Fraction of rated power and C rate have significance for non-flow BESSs; however, C rate is not very relevant for FBESSs since the energy content can be increased by increasing the electrolyte tank size for the same power engine (stacks). Since the energy-to-power ratio (E/P) ratio for the PSE and MESA1 BESSs are 2.2 hour and 0.5 hour, respectively, discharge at the maximum continuous rated power for the PSE BESS corresponds to a C/2.2 rate, while the equivalent rate is 2C for the MESA1 BESS. Hence, while the fractions of rated power used for both BESSs are in the same range of ~0.25 to 1, the C rates for the PSE system are in the C/6 to C/2.2 range and the C rates for MESA1 are in the C/4 to 2C range. This results in a wider performance range for MESA1 during each phase (baseline, post cycle 1, post cycle 2) of testing, while the PSE results during each phase are nearly identical across the C rates tested.

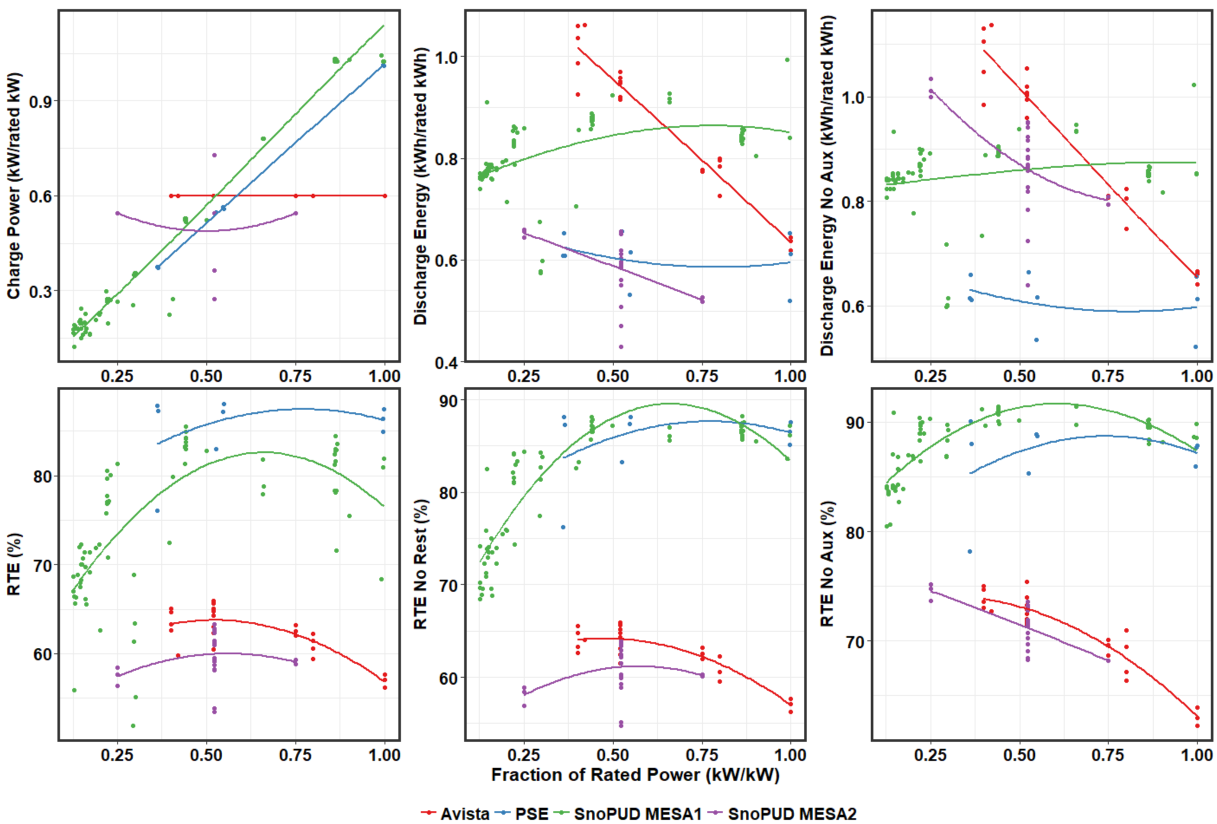

Figure 2.1. Metrics for Reference Performance Capacity Tests for All Utilities at Various Power Levels Represented as Fractions of Rated Power

As seen in Figure 2.1 and Figure 2.2, the RTE for the Li-ion BESSs at SnoPUD MESA1 and PSE follow a similar trend, as do the RTE for FBESSs at Avista and SnoPUD MESA2. The MESA2 FBESS performance was lower than the Avista FBESS performance due to a mismatch of available energy capacity among strings being compounded due to 2x the string count of the Avista FBESS.

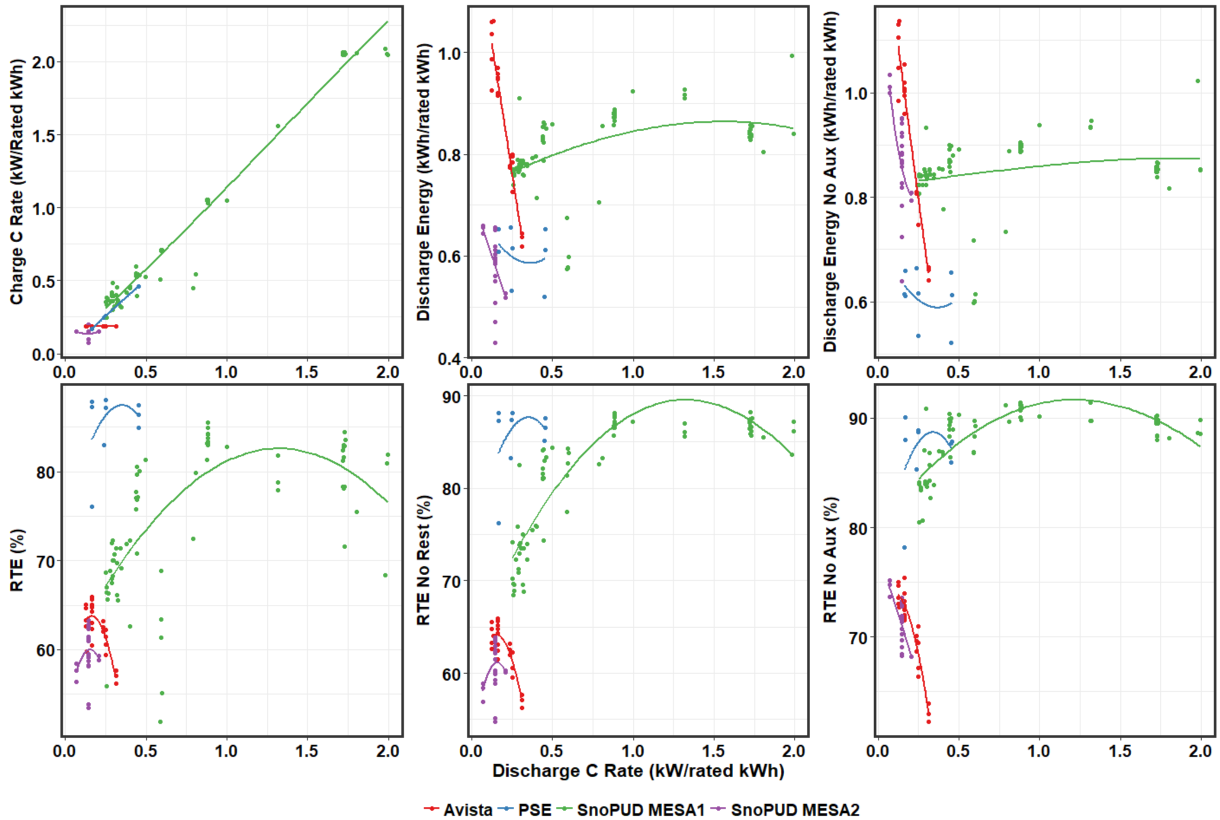

Figure 2.2. Metrics for Reference Performance Capacity Tests for All Utilities at Various Power Levels Represented as C Rates

The RTE for Li-ion BESSs is higher than that for FBESSs across the various rates examined. The MESA1 Li-ion BESS has an RTE peak at half the rated power or the 1C rate, related to the optimum operation regime in terms of temperature and power. At lower power levels, the lower temperatures lead to poorer performance, while at higher power levels, the higher operating temperature resulting in lower internal resistance is not sufficient to overcome the greater polarization losses associated with higher DC current. Temperature effects are more prominent for MESA1 than for PSE due to its significantly lower E/P ratio, resulting in the more pronounced RTE peak at the 1C rate. While temperature plays a key role in BESS performance, a holistic approach should consider the degradative effect of temperature. For FBESSs, the higher E/P ratio and greater thermal mass related to lower specific energy contribute to smaller temperature rise, resulting in increasing efficiency with decreasing discharge rates when auxiliary consumption is excluded.

For PSE, the maximum discharge energy measured at a DOD of 95% was 4,100 kilowatt-hours (kWh), much less than its rated energy of 4,400 kWh. Hence, the discharge energy at various C rates was low at 0.66 times rated energy. The SOC range for MESA1 was wider, in the 7.5 to 92.5% range. Hence, the discharge energy as a fraction of rated energy was higher for this BESS, at 0.83 to 0.90.

For the Avista FBESS, the delivered energy as fraction of rated energy increased as power decreased, ranging from 0.62 at rated power to 1.0 times rated energy at 0.4 times rated power. The corresponding numbers without auxiliary consumption are 0.66, 1.0, and 1.1, respectively. The MESA2 FBESS at 0.75 and 0.25 times rated power provided only 0.52 and 0.65 times rated energy, respectively, due to imbalance among strings. The corresponding numbers without auxiliary consumption are 0.8 and 1.0, respectively. This shows that balancing-related issues are less severe at lower rates, where the full rated energy could be obtained for MESA2 when auxiliary consumption is excluded.

Figure 2.3 shows the performance stability results. The Avista FBESS had stable performance through post cycle 2 tests. Performance stability could not be determined for the MESA2 BESS since the first cycle of use case testing was not completed.

The MESA1 Li-ion BESS was stable after one cycle of use case testing, The PSE Li-ion BESS had balancing-related issues that led to lower performance during post cycle 1 and post cycle 2 testing at the C/2.2 and C/4 rate. However, its performance was stable at the C/6 rate between post cycle 1 and post cycle 2, thus showing string to string imbalance was not a factor at low rates. This is in line with the findings for MESA2 FBESS, where string balancing-related effects were more pronounced at higher rates. While the reasons for string imbalance differ for FBESS versus Li-ion BESS, lower rate discharges alleviate this issue regardless of technology type (flow versus non-flow). As seen later in Figure 3.2, the internal resistance actually decreased during testing for PSE, probably due to a conditioning effect.

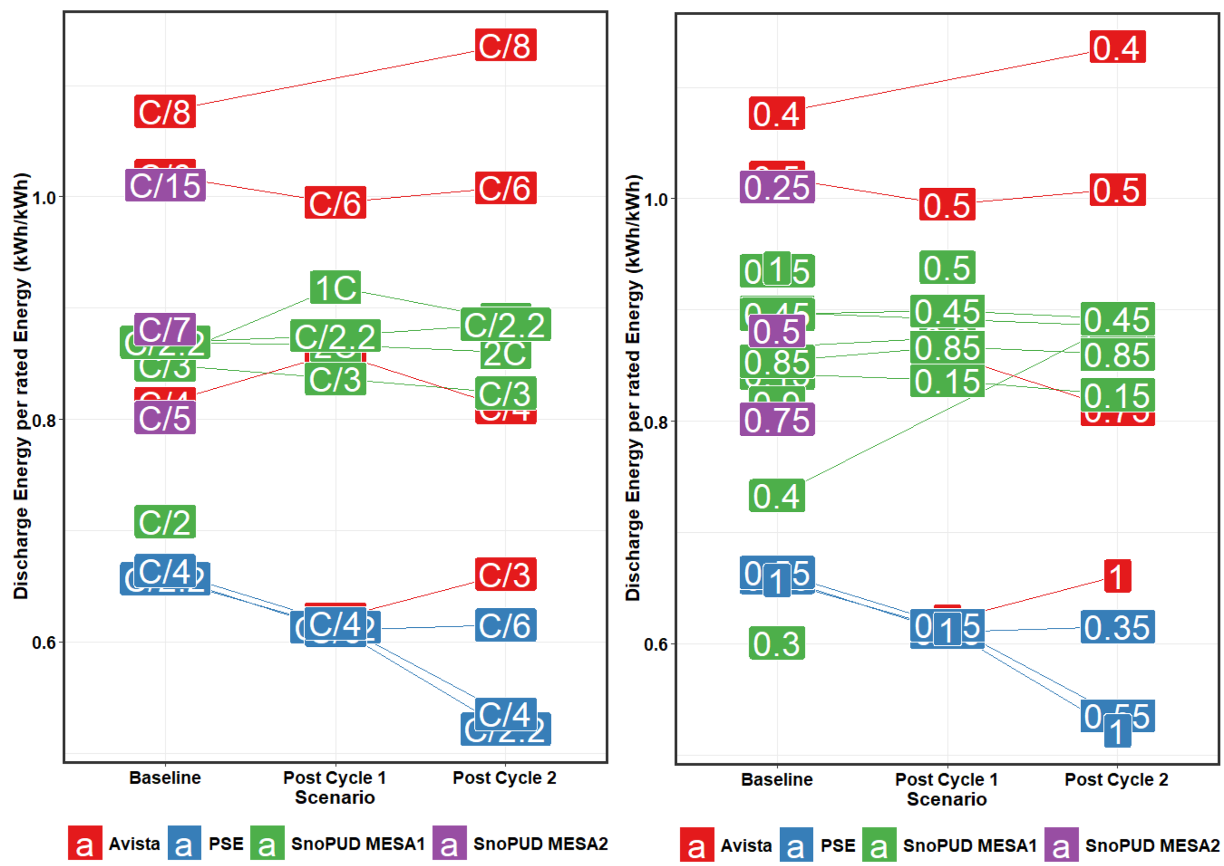

Figure 2.3. Discharged Energy as Testing Progressed for Utilities and C Rates; Left is Presented as C rate, Right is Presented in Terms of Fractions of Rated Power

3.0 Response Tests

The results of the response time/ramp rate testing are shown below in Table 3.1 and Figure 3.1, with each of the metrics given as a function of SOC. The fraction of rated power reached ranged from 0.35 to 1, with ramp rates in the 10 to 50% of rated power per second range, resulting in hardware response times of 2 to 10 seconds. The Li-ion BESS internal resistance, normalized with respect to power, was an order of magnitude lower than FBESS internal resistance.[3]

As discussed earlier for the MESA1 BESS, discharge pulse could be completed at only two SOCs, and charge pulse at one SOC. Since the data point resolution was only 10 seconds, and the BESS reached rated power within 10 seconds, the ramp rate was estimated to be faster than 10% of rated power per second.

For flow batteries, the discharge ramp rate for the Avista FBESS was about twice that for the MESA2 BESS in the 95 to 25% SOC range. While the Avista FBESS reached the target rated power, the MESA2 maximum power fell steeply to 50% of rated power at 30% SOC. The MESA2 resistance, adjusted on a MW basis, was about the same as Avista for both charge and discharge, and was one order of magnitude higher than the Li-ion BESS. Hence, the poorer peak power and ramp rate performance of the MESA2 FBESS can be assigned to string balancing-related issues.

The charge ramp rate for the FBESS was limited to 20% rated power per second by the battery management system (BMS). The target charge power was set to 80% of rated power, the vendor-recommended maximum continuous charge power. For the Avista FBESS, testing was done in the 20 to 95% SOC range, while for the MESA2 FBESS, testing was limited to the 12 to 55% SOC range due to string imbalance. The Avista FBESS reached the target power up to 60% SOC, above which the maximum power dropped linearly to 27% rated power at 95% SOC. Its ramp rate fell almost linearly from 20% of rated power per second at 20% SOC to 5% of rated power per second at 95% SOC. The MESA2 FBESS ramp rate remained steady at 20% of rated power per second in the 25 to 50% SOC range. This apparently superior MESA2 performance is misleading, since the maximum charge power attained for MESA2 was only 37% of rated power due to string balancing-related issues.

For the PSE BESS, the ramp rate was 25 to 50% of rated power per second for both charge and discharge, resulting in a response time of 2–4 seconds. Note that for PSE, a communication lag of 5 seconds was removed in order to assess the BESS hardware response. The target power was reached at all SOCs for charge and discharge pulses for both Li-ion BESSs. The internal resistance, normalized on the basis of MW rating, was 4 milliohms-MW for the PSE BESS, while it was 20 milliohms-MW for the MESA1 BESS, a factor of 20x and 4x lower than the FBESS internal resistance, respectively. As a rule of thumb, BESSs with high P/E ratios ideally would have DC modules with low internal resistance. The P/E ratio of the MESA1 BESS, at 2, is 4.5 times that of the PSE BESS, while its MW-normalized internal resistance is five times that of the PSE BESS. The product of P/E and MW-normalized internal resistance for MESA1 BESS is 22 times that of the PSE BESS. This indicates a mismatch between the power and energy rating, especially for the MESA1 BESS. Operation at the 2C rate for this higher resistance BESS could result in faster degradation.

[3] For the Avista and MESA 2 FBESSs, the target power was restricted to 0.8 times rated power during charge.

Table 3.1. Response Rate Test Results for Power, Ramp Rate, and Response Time

		Power (kW)				Ramp Rate (kW/S)				Response Time (s)				Resistance (mΩ-MW)			
Operation	SOC	Avista	PSE	SnoPUD MESA1	SnoPUD MESA2	Avista	PSE	SnoPUD MESA1	SnoPUD MESA2	Avista	PSE	SnoPUD MESA1	SnoPUD MESA2	Avista	PSE	SnoPUD MESA1	SnoPUD MESA2
Charge	0	NA	2077	NA	NA	NA	520	NA	NA	NA	4	NA	NA	NA	5	NA	NA
Charge	10	NA	2076	2000	800	NA	778	200	200	NA	3	10	4	NA	5	24	45
Charge	20	762	2076	NA	800	191	1033	NA	400	4	2	NA	2	112	4	NA	42
Charge	30	792	2076	NA	800	158	1038	NA	400	5	2	NA	2	106	4	NA	41
Charge	40	777	2075	NA	799	129	1037	NA	333	6	2	NA	3	102	4	NA	40
Charge	50	775	2074	NA	799	111	1032	NA	300	7	2	NA	3	102	4	NA	39
Charge	60	753	2075	NA	NA	75	1032	NA	NA	10	2	NA	NA	99	4	NA	NA
Charge	70	623	2080	NA	NA	78	1038	NA	NA	8	1	NA	NA	97	2	NA	NA
Charge	80	NA	1817	NA	NA	NA	614	NA	NA	NA	5	NA	NA	NA	4	NA	NA
Charge	90	459	NA	NA	NA	51	NA	NA	NA	9	NA	NA	NA	97	NA	NA	NA
Charge	100	292	NA	NA	NA	58	NA	NA	NA	5	NA	NA	NA	95	NA	NA	NA
Discharge	0	NA	2041	NA	NA	NA	1021	NA	NA	NA	2	NA	NA	NA	5	NA	NA
Discharge	10	NA	2038	NA	NA	NA	509	NA	NA	NA	2	NA	NA	NA	6	NA	NA
Discharge	20	NA	2045	NA	1100	NA	512	NA	321	NA	4	NA	4	NA	4	NA	46
Discharge	30	946	2046	NA	1100	315	511	NA	275	3	4	NA	4	122	4	NA	41
Discharge	40	1000	2045	2000	NA	333	511	200	NA	3	4	10	NA	110	6	18	NA
Discharge	50	1010	2041	NA	NA	337	1020	NA	NA	3	2	NA	NA	108	4	NA	NA
Discharge	60	1015	2030	NA	2200	338	763	NA	550	3	2	NA	4	100	4	NA	47
Discharge	70	1018	2035	NA	2200	339	764	NA	440	3	3	NA	5	101	5	NA	44
Discharge	80	NA	2036	2000	NA	NA	1018	200	NA	NA	2	10	NA	NA	4	16	NA
Discharge	90	1020	2019	NA	2200	340	505	NA	550	3	4	NA	4	101	4	NA	42

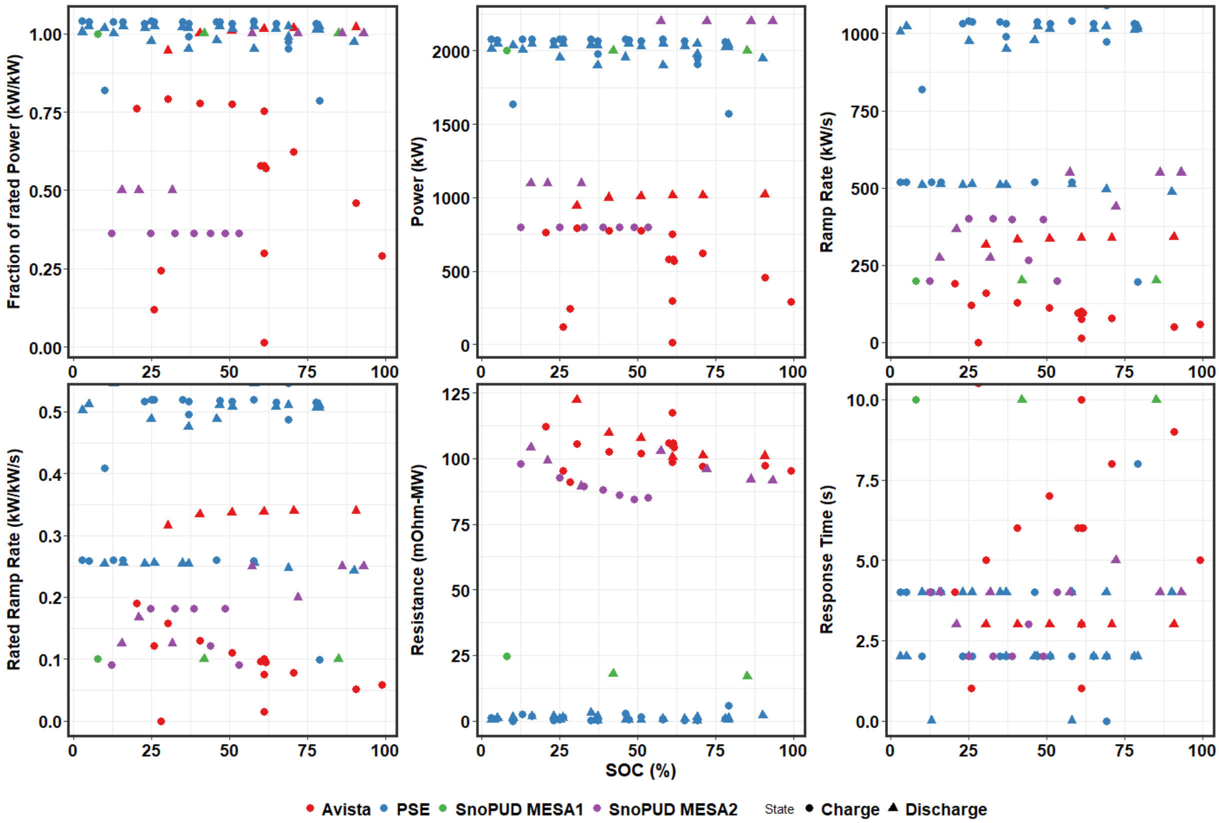

Figure 3.1. Response Test Results for All Utilities

The internal resistance of a battery can be measured by various methods. One way is to pulse the battery at high rates and measure the change in voltage (ΔV) after a fixed duration. Depending on the duration, the ΔV would be different, resulting in different reported internal resistances. At high durations, the ΔSOC would be high, resulting in high reported internal resistance, part of which is due to the change in SOC.

The internal resistance was reported in accordance with the provisions in Section 7.2 of the test plan report (Viswanathan et al. 2017). This test is done as part of baseline testing, and as part of an RPT after use case testing. Results are shown for 10-second 1C rate pulses, which correspond to ΔSOC <0.1%.

Note that for SnoPUD MESA1, the data was in 10-second resolution, and commands could only be sent with 15-minute resolution, meaning that we could not investigate many SOCs or accurately measure response time.

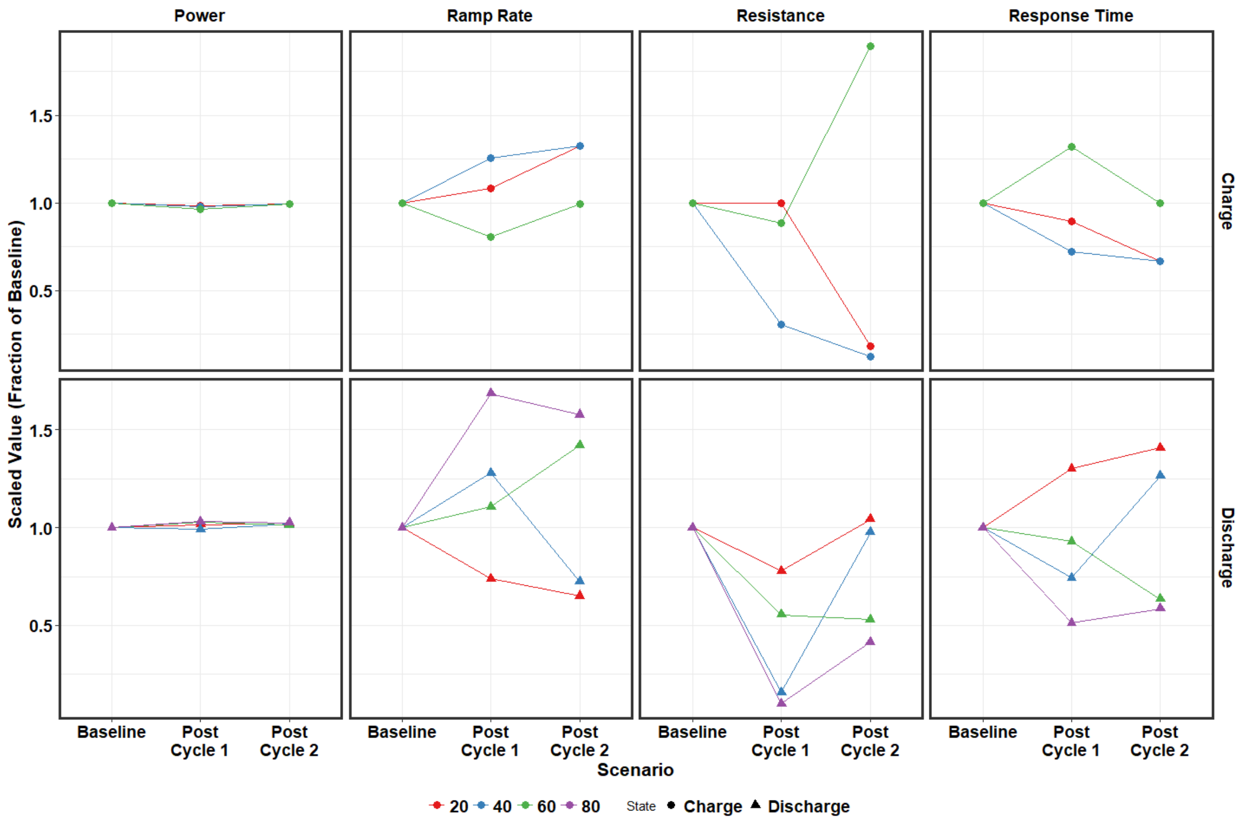

Figure 3.2. Stability of Power Related Metrics for PSE BESS

Baseline results for response time tests for the Avista FBESS were lost due to a data hole, while RPT tests post cycle 1 were not conducted for MESA1. The MESA2 FBESS did not finish cycle 1 testing. Hence, stability data for these power related metrics were available only for the PSE BESS. Figure 3.2 shows the results for discharge pulses at 20, 40, 60, and 80% SOC. The discharge resistance at 20, 40, and 80% SOC was at a minimum after cycle 1, while at 60% SOC, it decreased with test duration. The ramp rate, for the most part, was a mirror image of the resistance, increasing when the resistance decreased and vice versa, while the response time increased with increasing resistance. For all phases of testing, the target rated discharge power was reached.

During charge, the resistance decreased with test duration for 20 and 40% SOC, with a corresponding increase in ramp rates, while resistance increased after cycle 2 testing at 60% SOC. The results show that there is a conditioning effect at moderate SOC changes, with improvement in performance for both discharge and charge pulses, with onset of degradation after cycle 1 for discharge and for high SOC charge. This information is useful to ensure an appropriate operating envelope as the BESS ages.

4.0 Reference Performance Frequency Regulation Tests

The FBESSs were subjected to the 24-hour DOE-OE Frequency Regulation Signal as part of the RPT. For the Avista FBESS, the power unit was set to 800 kW, the rated continuous charge power, while for the PSE BESS, one power unit was set to be equal to the rated power of 2,000 kW. Note that for the SnoPUD MESA2 FBESS, power requests could be sent only every 15 minutes, whereas for the PSE and Avista BESS, commands could be sent every 4 seconds. This means the reported signal tracking performance is artificially higher for SnoPUD MESA2. On the other hand, due to a string dropping off before testing started, the requested power was twice the intended power, resulting in poor signal tracking. Analysis for MESA2 was done by multiplying the FBESS response by 2 to account for the dropped string.

The error distribution is given in Figure 4.1, with error presented in terms of fraction of rated power on the x-axis. Again, note that SnoPUD MESA2's artificial peak at the origin is due to the 15-minute resolution of the signal. Comparing Avista and PSE's error without auxiliary loads, Avista has a sharper peak near the origin, meaning Avista has more points with low error. However, PSE has a smaller root mean square error (RMSE) due to having smaller magnitudes of error overall. The negative bias is due to auxiliary consumption. As seen in Table 4.1, the normalized RMSE is 2–3% of rated power for the PSE and Avista BESS, with slight improvements when auxiliary consumption is excluded. As expected, the RTE for FBESSs is lower than for the Li-ion BESS at PSE.

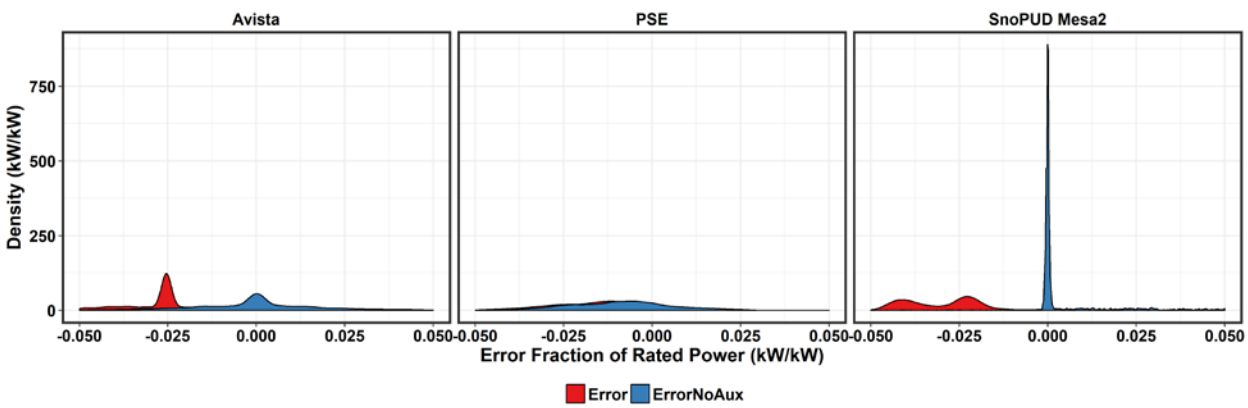

Figure 4.1. Distribution of Error During Baseline Frequency Regulation Tests

Table 4.1. Reference Performance Frequency Regulation Test Results

Parameter	Avista	PSE	SnoPUD MESA2
Norm. RMSE	0.032	0.020	0.171
Norm. RMSE No Aux	0.026	0.018	0.166
Tracking within 2% of Rated Power	0.24	0.97	0.82
Signal Tracking within 2%	0.55	0.44	0.65
RTE (%)	60.9	81.4	50.3
RTE No Aux (%)	72.2	83.2	57.5

5.0 Use Case Analysis

Various use cases were tested for each utility (see Table 1.2). A comparison of performance for use cases common to all utilities is given in the following sections.

5.1 Use Case 1 – Arbitrage

The energy arbitrage duty cycle was modeled using PNNL's Battery Storage Evaluation Tool by maximizing BESS revenue for a one-week period using historic Mid-Columbia wholesale energy price data. For arbitrage, the RTE is the most useful metric; see Figure 5.1 for a comparison of average discharge power. RTE ranged from 45 to 90% in the use case for Avista, PSE, SnoPUD MESA1, and SnoPUD MESA2.

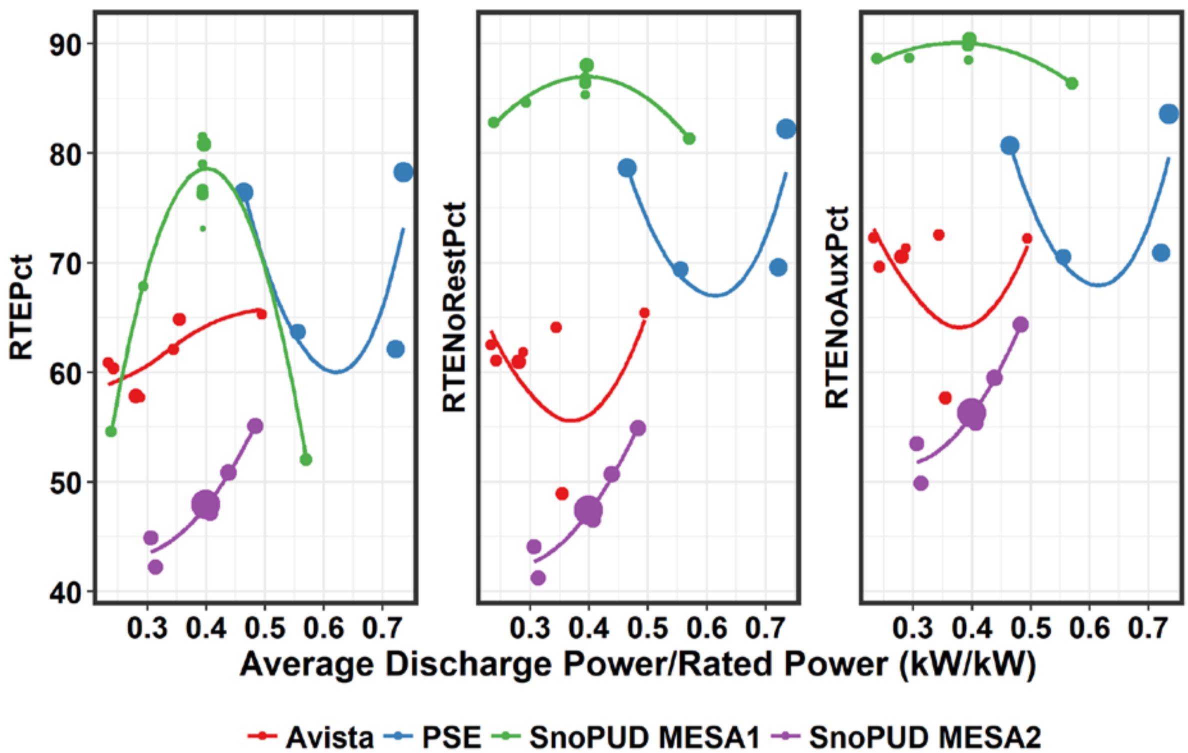

Figure 5.1. Arbitrage Use Case Round Trip Efficiencies

The rest durations at SnoPUD MESA1 and PSE during arbitrage cycles were 80% of the total test durations; rest durations for Avista were at 20% and for SnoPUD MESA2 were close to 0%. Hence, the RTE without rest was unchanged for MESA2, marginally higher for Avista, and significantly higher for MESA1. Since auxiliary consumption at PSE was about three times lower than at MESA1, even though both had the same rest percent, RTE increased only marginally at PSE when rest was excluded. The greatest increase in RTE while excluding auxiliary consumption was for the Avista and MESA2 FBESSs, while the lowest was for the PSE BESS; this was in line with auxiliary consumption at each site as a fraction of rated power.

The FBESS RTE was lower than the Li-ion BESS RTE. The MESA2 RTE was the lowest and decreased with reductions in power even after excluding auxiliary consumption. This may be due to a greater self-discharge rate for MESA2, possibly due to a higher electrolyte crossover rate, which is more significant at lower power levels. A recommendation for future work will be to compare coulombic efficiency for the MESA2 FBESS with the Avista FBESS. Even though UniEnergy Technologies is moving to 10 kW modular units, this work may be useful to obtain a holistic picture of why the RTE continues to drop with decreasing power levels even after auxiliary consumption is excluded. The SOC range of operation also affects RTE, especially for FBESSs. Future work will also compare the SOC range for the Avista and MESA2 FBESS to explain the discrepancy in RTE, especially at low rates.

The low E/P ratio for the MESA1 BESS required using a low percent of rated power for some runs. This, coupled with long rest durations, dropped the RTE to as low as 55%. Excluding rest time, the RTE was much higher (82%). Since the PSE BESS was not used at <0.45 times rated power due to its high E/P ratio, this adverse effect of power levels at a low fraction of rated power was not observed for the PSE battery. This indicates the obvious—batteries with low E/P ratios are not well suited for long duration applications that require them to operate at a low percent of rated power, especially if their auxiliary consumption is a high fraction of rated power. There were some runs where the MESA1 BESS was operated at 0.6 times rated power (or 1.2C rate). These runs also resulted in a low RTE, since the low E/P ratio results in a low charge and discharge duration, with rest time dominating the total test duration. As expected, the RTE increased when rest was excluded. Considering the low E/P of this BESS, it should not be placed in rest mode for extended periods. The option to place the BESS in standby mode with a potentially lower auxiliary consumption should be explored for all operations with long idle times. To this end, information on auxiliary consumption during standby mode should be made available.

The results demonstrate the effect of technology, E/P ratio, and rest duration on performance. They also emphasize the need to keep the BESS in operation for other use cases instead of being idle, with the rest duration limited to lower values for BESS with high auxiliary consumption and/or low E/P ratios.

5.2 Use Case 1 – System Capacity

System capacity or resource adequacy is a peak shaving operation triggered by system-wide peak load conditions. To determine the hours when energy storage would be needed to provide capacity services, hourly system-wide load data was obtained for the most recent year. The RTE as a function of average discharge power is shown in Figure 5.2 for this use case.

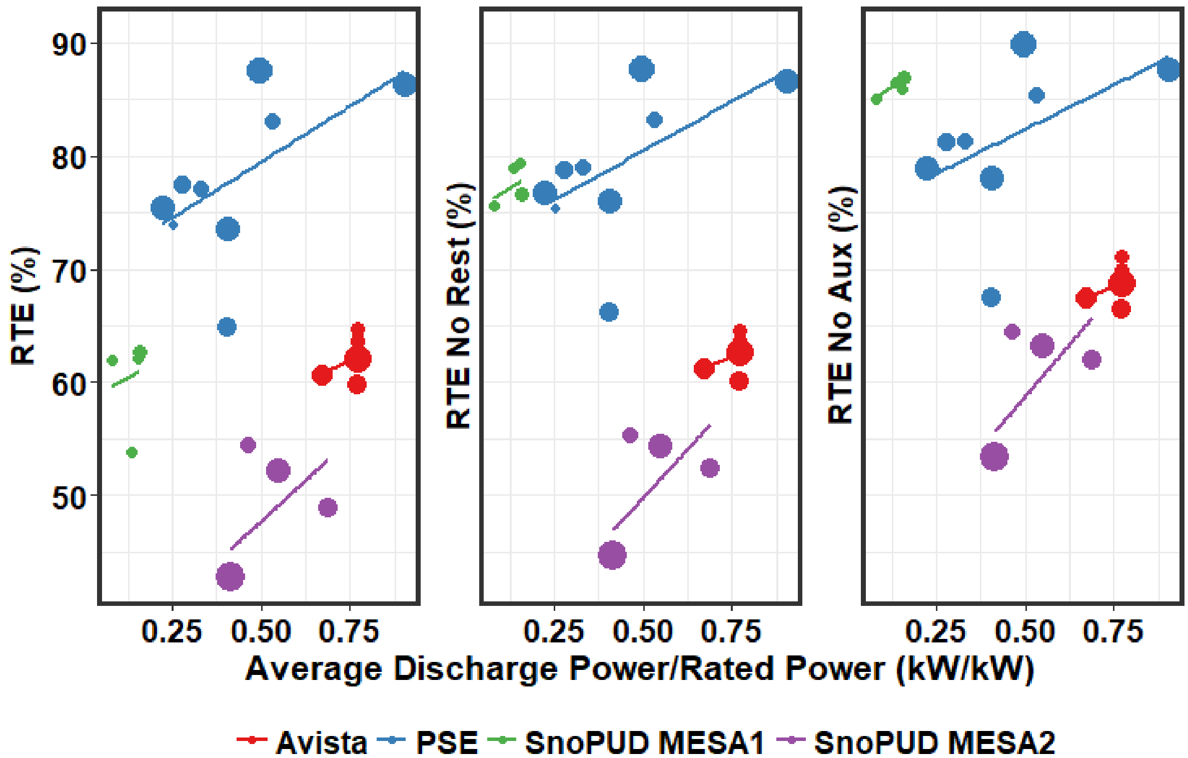

Figure 5.2. Capacity Use Case Round Trip Efficiencies

Capacity triggers are defined differently for each utility. For SnoPUD, the capacity duty cycle assumed a 4 hour peak shaving requirement, which is a standard industry requirement and was confirmed as reasonable by SnoPUD staff. Based on the data provided by Avista, PNNL defined an hourly duty cycle that provided 6 hours of capacity each day, discharging during the peak loads for the day. For PSE, the capacity duty cycle was developed as a 7 day schedule of charging/discharging power with discharge periods varying from one to four during peak hours and charging adequately to maintain SOC.

Similar RTE trends are noted for all sites, with RTE decreasing with decreasing discharge power. As seen earlier for Li-ion BESSs, lower power levels correspond to lower operating temperatures; this results in low RTE even when auxiliary power is excluded. Due to the low E/P ratio for the MESA1 BESS, its runs were done at a low fraction of rated power (~0.08 to 0.1 times rated power). Hence, its RTE was much lower than the PSE BESS and was in line with the Avista FBESS, which was operating at much higher fractions of rated power. The PSE BESS with an E/P of 2.2 has an operating power range of 0.25 to 1 times rated power. As seen in RPT, the RTE decreased with decreasing power for Li-ion BESSs due to a lower average temperature of operation.

The Avista FBESS, with an E/P of 3.2, was operated within a narrow power range of 0.63 to 0.76 times rated power, while the MESA2 FBESS, with an E/P of 4, had a lower operating power range of 0.4 to 0.65 times rated power. While the RPT test showed increasing RTE with decreasing power for FBESSs when auxiliary consumption was excluded, the reverse was true for arbitrage for the MESA2 FBESS. Closer inspection showed that the average SOC was lower for the lower power runs. Flow battery efficiency in this work decreases with a decreasing SOC range due to linearly decreasing OCV as SOC decreases, resulting in greater current flow during discharge for a given power. Additionally, optimized flow control as a function of operation mode, temperature, and SOC is needed to reduce losses at extreme SOCs during charge and discharge. Without access to flow rate information as a function of operating parameters, it is not possible to determine the contributions due to mass transport related losses at extreme SOCs. It is recommended that analysis of DC curves be done to assign loss contributions to various buckets, such as ohmic, charge transfer, and mass transport.

This work demonstrates the multiple factors that impact RTE—power, mode, temperature, and SOC range of operation. While a flow battery performance model is useful in determining a priori what is to be expected, it needs to be adjusted any time the BESS system design is modified. For example, optimization of flow control would result in different performance for the same FBESS.

5.3 Use Case 2 – Regulation

The duty cycle for this test is developed by scaling down the area control error signal (MW) provided by the utility using a response factor (kW/MW) to match the rated power capacity of the BESS. The BESS was discharged (or charged) to bring the SOC down to a specific level before the start of the next run.

As seen in Figure 5.3, the response is within 3% of rated power for the Avista and PSE BESS, with a negative bias for the peaks, as expected, when auxiliary consumption is included. Excluding auxiliary consumption, the peak occurs at close to 0 kW error, with the PSE BESS still having a slight negative bias. Both BESSs have a long tail when auxiliary consumption is included, which disappears, as expected, when excluding auxiliary consumption. While reference signal tracking is the key metric for this use case, RTE is also relevant. Figure 5.4 illustrates the relative performance. There seems to be a weak relationship between the RMSE and the average discharge power, as seen in Figure 5.5, with an increased discharge power increasing the RMSE.

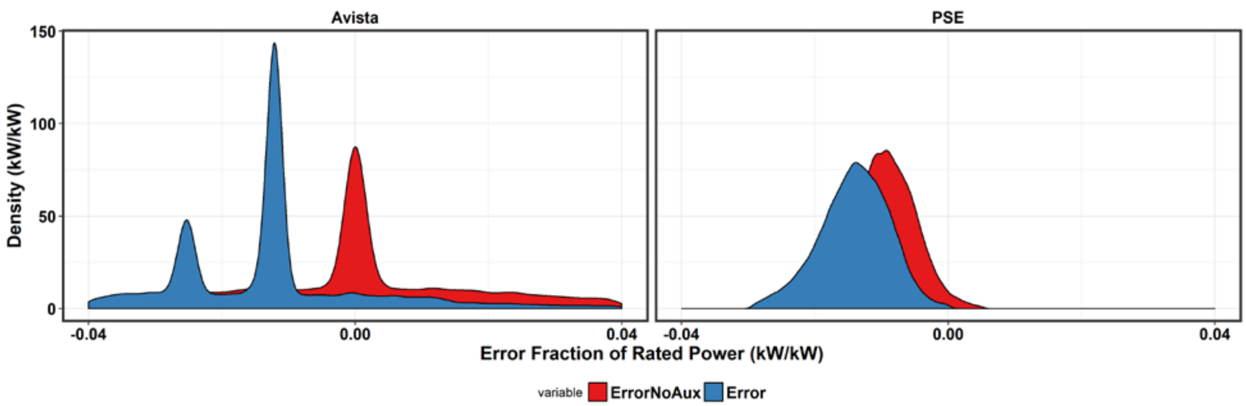

Figure 5.3. Distribution of Error for Regulation Use Case Tests

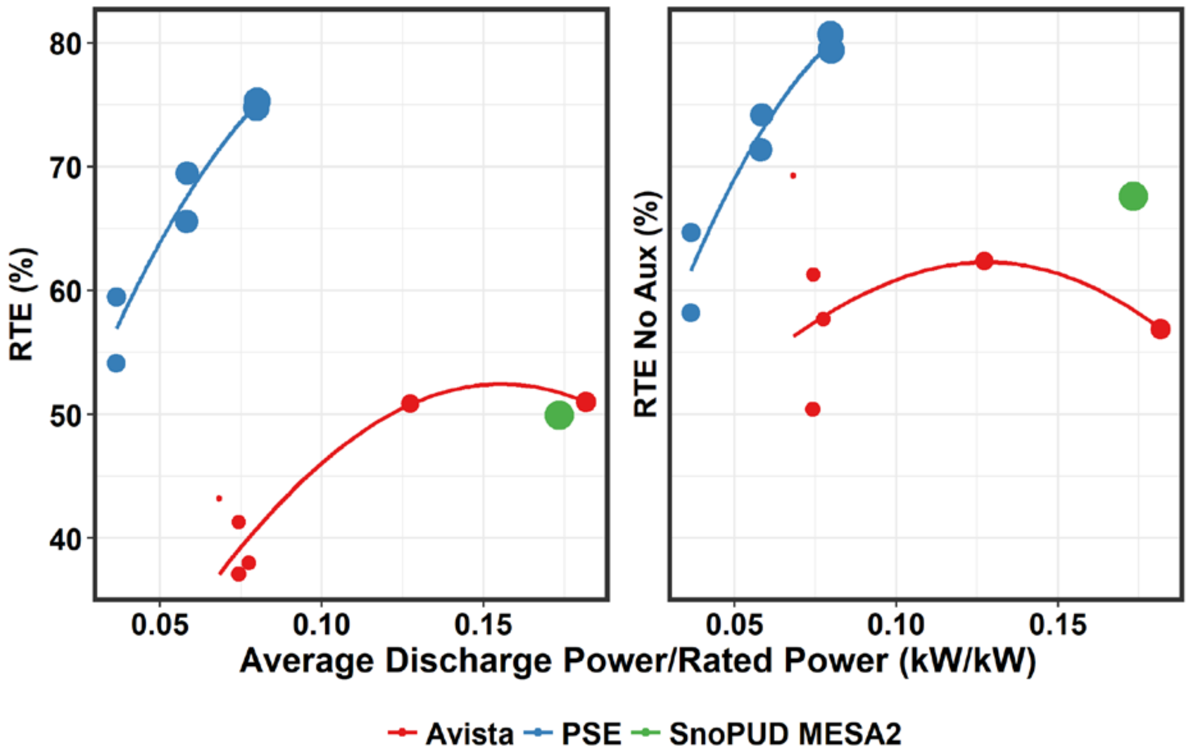

Figure 5.4. Round Trip Efficiency during the Regulation Use Case

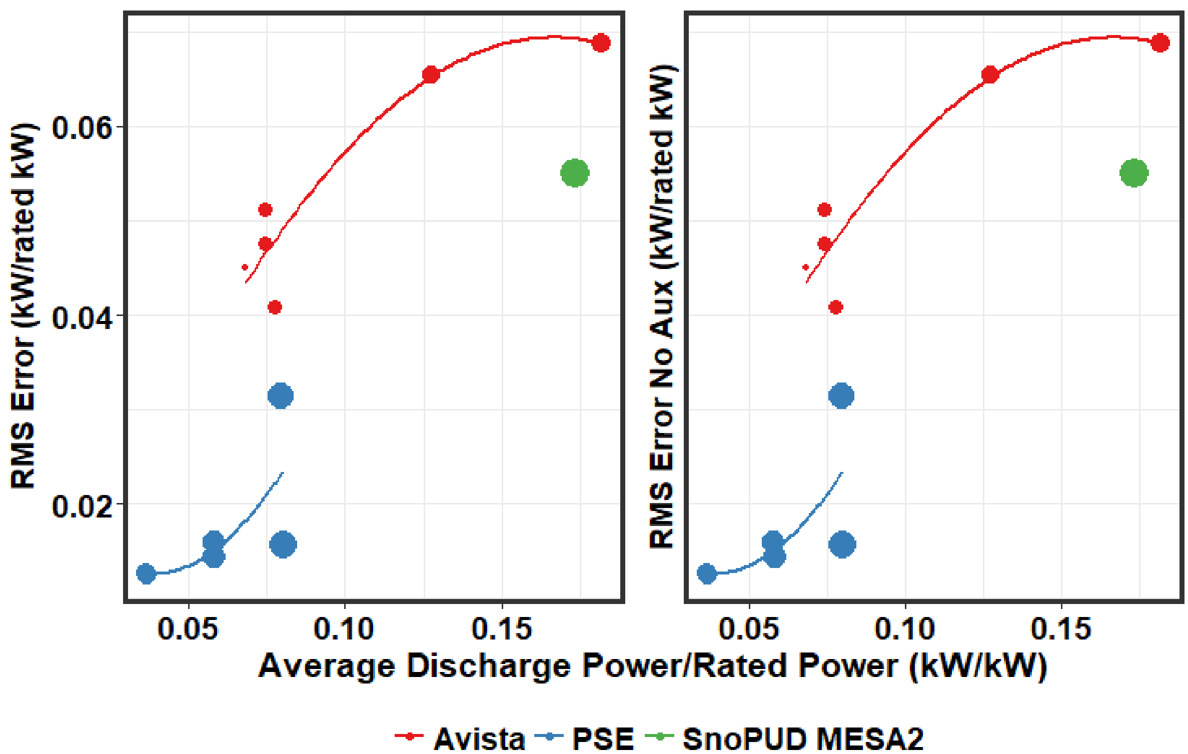

Figure 5.5. Root Mean Square Error during the Regulation Use Case

The average power levels extend to very low fractions of rated power—0.04 times rated power for PSE and 0.07 times rated power for Avista. At these low power levels, auxiliary consumption alone is expected to limit the PSE BESS RTE to 85%, and the Avista FBESS RTE to 36%. The RTE for the PSE BESS is 60% at low power, and the Avista FBESS RTE is 40% (Figure 5.4). Once auxiliary consumption is excluded, the RTE increases to 65% and 55%, respectively, limited in this case by power conversion system (PCS) efficiency at these low power levels.

The normalized RMSE increases slightly with increases in power, but is quite low, at 1.5 to 3% of rated power for the PSE Li-ion BESS and 4 to 7% of rated power for the Avista FBESS, with the one data point for MESA2 at 5.5% of rated power.

SnoPUD MESA2 is excluded from Figure 5.3 and Figure 5.4 due to its 15 minute signal resolution artificially reducing the error.

5.4 Use Case 2 – Load Following

The duty cycle for this test was developed by smoothing the regulation duty cycle (which has a time resolution of 4 seconds), applying a moving average with a 5 minute window. The resulting signal still has a 4 second time resolution but is much less volatile.

As seen in Figure 5.6, the response is within 3% of rated power for the Avista and PSE BESS, with a negative bias for the peaks as expected when auxiliary consumption is included. Excluding auxiliary consumption, the peak occurs at close to 0 kW error, with the PSE BESS still having a slight negative bias. Smoothing the regulation duty cycle reduces the long tail for the Avista FBESS and eliminated the tail for the PSE BESS.

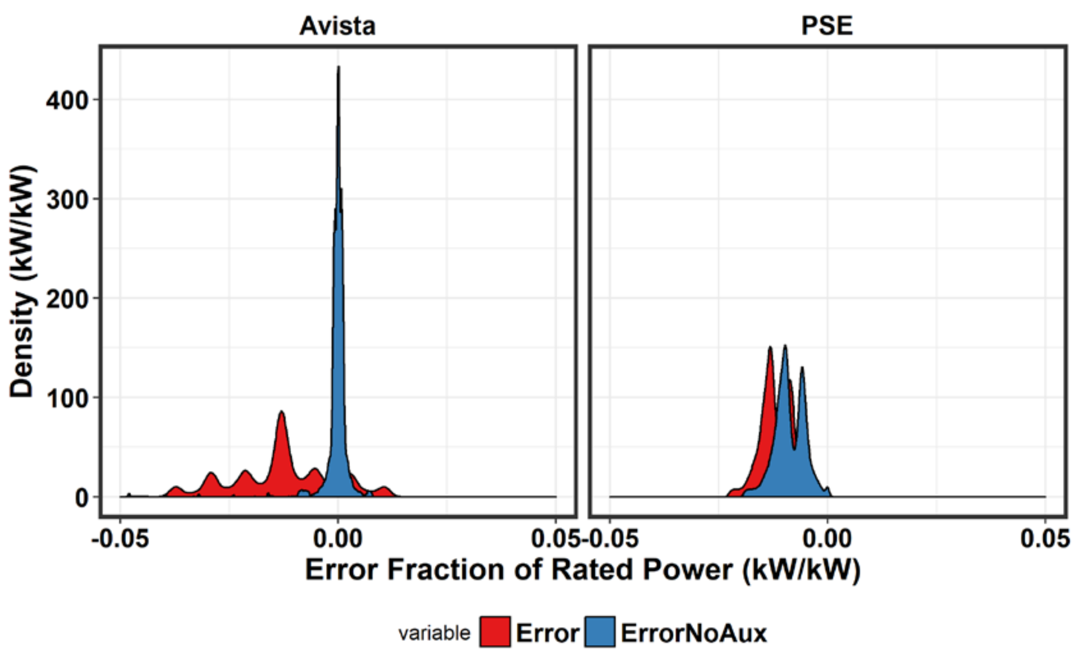

Figure 5.6. Error Distribution for Load Following Use Case

The relative performance based on measured RTE for this use case is shown in Figure 5.7. The RTE for PSE decreases, as expected, with decreasing power levels due to low PCS efficiency at low average power levels of 0.03 times rated power.

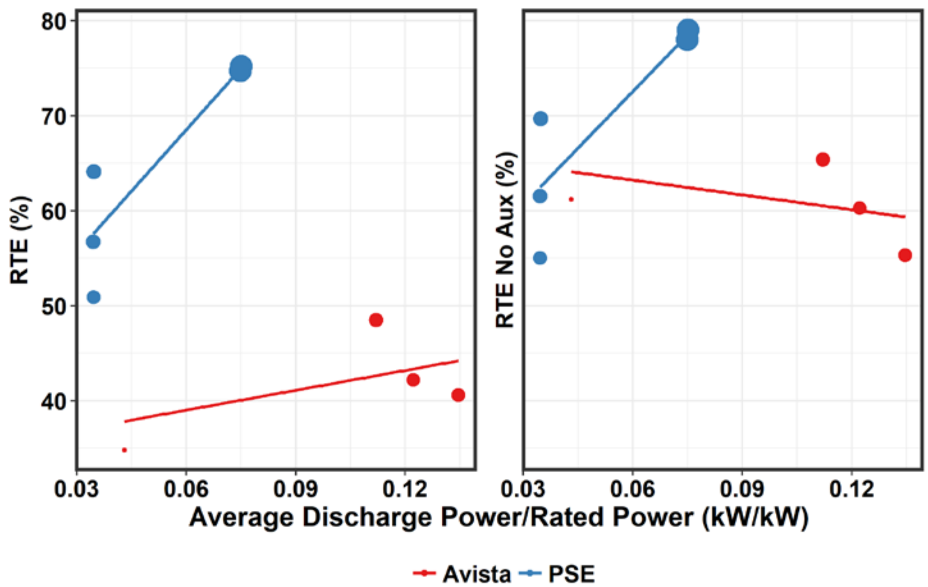

Figure 5.7. Round Trip Efficiencies for Load Following Use Case

5.5 Use Case 3 – Load Shaping

This use case could be tested in several ways (e.g., limiting load within a certain threshold or limiting rate of change of load with time), hence there are differences in this duty cycle for each utility.

For Avista, this test was conducted by limiting fast variations of feeder load. Using historical 10 second or faster feeder load data from 2011–2015, a low-pass filter designed by PNNL was implemented by Avista. The current feeder load was fed through this filter and the difference in the filtered feeder load was used to define the current ramp rate of the feeder.

The load-shaping duty cycle for SnoPUD was developed in the Battery Storage Evaluation Tool by minimizing the balancing payment to the Bonneville Power Administration (BPA). The duty cycle required to minimize the BPA payment is composed of varying levels of charges and discharges dependent on the gap between scheduled and actual load demand and energy price. Minimizing the balancing payment while maintaining the SOC between 10 and 90% produced an optimum charge/discharge schedule.

For PSE, peak load shaving to defer distribution upgrades and load ramp rate control to manage renewable integration are not issues of immediate concern on the test feeder. Instead, load shaping is used to reduce the gap between the peak and valley of the daily load profile. Distribution system operators need to engage resources (e.g., voltage regulator/tap changer/capacitor bank operation) to mitigate the impact of this gap daily. Using storage to “flatten” daily load profiles could provide some benefit by reducing voltage regulator, tap changer, and capacitor bank operation.

The load-shaping use case test results are presented in Figure 5.8. The lower RTE for the PSE BESS compared to the MESA1 BESS is due to its average power levels being much lower, leading to low PCS efficiency. Considering that the E/P ratio of PSE is 4.4 times that of MESA1, and the percent rated power is ~15 times lower than that for MESA1, it is indicated that the duration for charge or discharge operation for PSE is 65 times longer than that for MESA1 for this use case. This is an extreme case. In general, it would be expected that the MESA1 BESS would be subject to lower power levels due to its lower E/P ratio.

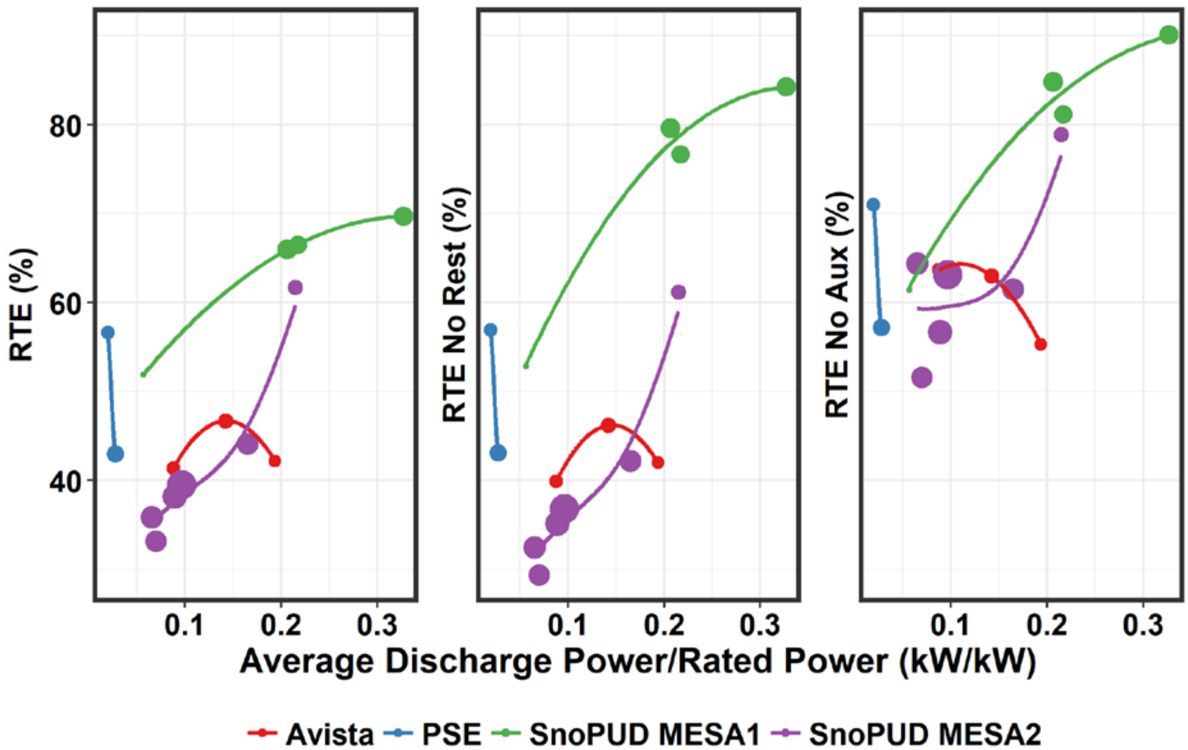

Figure 5.8. Load-Shaping Use Case Round Trip Efficiencies

The FBESS RTE decreases with decreasing power levels in the 0.06 to 0.22 times rated power range due to the higher auxiliary contribution as power decreases. When auxiliary power is excluded, the Avista and MESA2 FBESSs behave differently. The Avista FBESS average SOC increases with decreasing power levels, resulting in increasing RTE; the reverse is true for the MESA2 FBESS.

6.0 Auxiliary Power

Each BESS had auxiliary power requirements to operate, with different needs for FBESSs and Li-Ion BESSs. FBESSs always require pumping power, and the Li-ion BESSs in this study used active heating and cooling systems for thermal management in contrast to the FBESSs which only had cooling. Table 6.1 shows a summary of the components requiring auxiliary power and the data acquired for each system.

Table 6.1 Auxiliary System Summary

Utility	Aux meter	Time resolution (s)	Components powered by aux
Avista	No	10	Pumps, instruments, PCS control, lighting, BMS control, cooling
PSE	Yes	4	Cooling, heating, instruments, PCS control, lighting, BMS control
SnoPUD MESA1	Yes	10	Cooling, heating, instruments, PCS control, lighting, BMS control
SnoPUD MESA2	No	1	Pumps, instruments, PCS control, lighting, BMS control, cooling

The auxiliary power was measured and modeled in slightly different ways for each system. For PSE and SnoPUD MESA1, the auxiliary meter data were available. For Avista and SnoPUD MESA2, this was not available and had to be approximated by taking the difference between the power at the battery and the power at the grid.

- Avista – Auxiliary load was modeled as a function of battery temperature, power, and power squared.
- PSE – Auxiliary load was modeled as a piecewise function of battery temperature at various locations and at ambient temperature.
- SnoPUD MESA2 – Auxiliary load was modeled as a function of battery temperature, power, and power squared (but regressed separately).
- SnoPUD MESA1 – Auxiliary load was not modeled.

Due to the different independent variables used for modeling, individual results are not presented. Table 6.2 shows the average auxiliary power consumption for each utility. As expected, FBESSs have greater auxiliary consumption, since an electrolyte must be continuously pumped through the stacks. The FBESS auxiliary consumption is nearly an order of magnitude greater than the value for the PSE BESS and is about three times that for the MESA1 BESS. The nearly 4x greater auxiliary consumption for MESA1 compared to the PSE BESS is likely due to its high P/E ratio, its higher MW-normalized resistance, and the higher C rates at which it was operated, leading to a greater cooling load.

Table 6.2. Average Auxiliary Power Consumption

	Avista	PSE	SnoPUD MESA1	SnoPUD MESA2
Mean Auxiliary (kW/rated kW)	0.028	0.004	0.011	0.036
Standard Deviation Auxiliary (kW/rated kW)	0.007	0.002	0.005	0.007

7.0 PCS Losses

PCS losses are the difference between the alternating current power at the inverter and the DC power at the battery; these losses are shown in Table 7.1 and Figure 7.1. Although the Avista and MESA2 FBESSs use the same AEG Power Solutions inverter, the Avista PCS is more efficient during discharge, while the reverse is true for the MESA2 PCS. The PSE inverter is more efficient during charge and least efficient at low power levels. The MESA1 inverter losses are lower during discharge, with the efficiency peaking at 0.5 times rated power. These PCS characteristics determine the optimum charge and discharge rates to be used for various use cases.

Table 7.1. Normalized PCS Losses at Various Normalized Power Levels

Utility	Intercept	Power	Power Squared
Avista	0.0138	-0.0049	0.0157
PSE	0.0189	0.0854	0.0320
SnoPUD MESA1	0.0088	-0.0158	0.0141
SnoPUD MESA2	0.0112	0.0129	0.0222

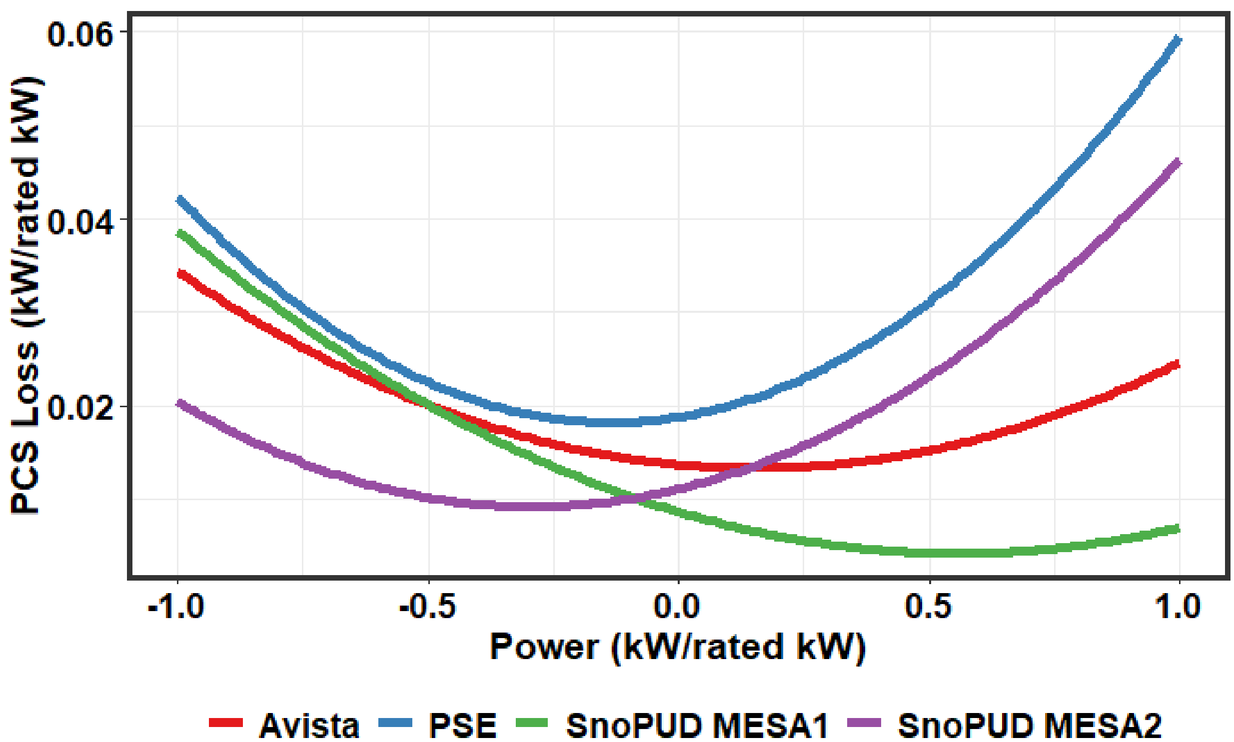

Figure 7.1. PCS Losses Regression

8.0 Thermal Modeling

Thermal modeling was completed for each BESS to estimate how the temperature changes with time. All four BESSs had their rate of temperature change results regressed vs. power and power squared, with the power providing the heat change due to enthalpy and the power squared providing the heat change due to ohmic heating. The difference between the battery temperature and the ambient temperature based on local weather stations was also incorporated, representing Newton's law of cooling. These results are provided in Table 8.1.

Table 8.1. Thermal Coefficients for Modeling

Parameter	Avista Estimate	Avista Uncertainty	PSE Estimate	PSE Uncertainty	SnoPUD MESA1 Estimate	SnoPUD MESA1 Uncertainty	SnoPUD MESA2 Estimate	SnoPUD MESA2 Uncertainty
Del Temp ((C/h)/C)	-4.81E-01	2.5E-02	-6.03E-03	1.3E-04	-1.07E-02	1.0E-04	-2.71E-02	1.6E-03
Power ((C/h)/kW)	1.11E-03	3.0E-06	-3.62E-04	2.9E-06	-6.92E-05	3.2E-06	6.66E-04	1.2E-06
Power^2 ((C/h)/kW^2)	2.81E-07	8.4E-09	5.36E-07	3.7E-09	4.68E-06	6.6E-09	2.29E-07	1.5E-09

The entropic effect is endothermic during charge for flow batteries and during discharge for Li-ion batteries, as seen by the coefficient of power. As expected, all three utilities have a positive coefficient for the power squared term. While the results are not shown, similar results were obtained when the DC power was used in the calculations.

The rate of change of temperature as a function of power is shown in Figure 8.1. For the PSE Li-ion BESS, the endothermic effect of discharge results in cooling at power levels less than 0.3 times rated power, or 0.14 C rate, while the corresponding value for the MESA1 BESS is 0.04 times rated power, or 0.14 C rate. In other words, the C rate at which transition from heating to cooling occurs is the same for both Li-ion BESSs. At greater power levels, the I^2R term overwhelms the endothermic effect.

For the FBESSs, the endothermic entropic effect during charge overwhelms the I^2R term in the charge range investigated. Hence, charge is accompanied by cooling, while discharge is accompanied by heating across the power range investigated. As expected, the rate of cooling decreases as charge power increases due to the higher contributon of the I^2R term. The FBESSs have a thermal mass that is approximately five times that of the Li-ion BESS for a fixed energy content due to its approximately five times lower specific energy. Additionally, the E/P ratio of the FBESSs, at 3.2–4, is higher than the 0.5 value for the MESA1 BESS and the 2.2 value for the PSE BESS.

Table 8.2 shows that the system mass per unit kW for FBESSs is ~35 times MESA1 and approximately eight times the PSE BESS. However, accounting for normalized internal resistance, the MESA1 BESS shows the highest number for the ratio of MW-normalized resistance to the estimated system mass for 1 MW. The higher this number, the higher the rate of temperature rise for unit change in power. Note that the rate of rise of temperature is highest for the MESA1 BESS, as expected. Note that the last column in Table 8.2, the product of P/E and MW-normalized resistance, is a proxy for the rate of temperature rise. However, since the mass per unit kW is different for flow versus Li-ion BESSs, this column should be used only when comparing the rate of change of temperature within a battery technology. This column can be used across technologies to determine the influence of the I^2R term—the higher this number, the greater the influence of ohmic heating. The net cooling during charge apears to indicate that the entropic term for the FBESSs is greater than that for the PSE Li-ion BESS, since it overwhelms the higher expected I^2R term for the FBESSs based on the values in the last column of Table 8.2.

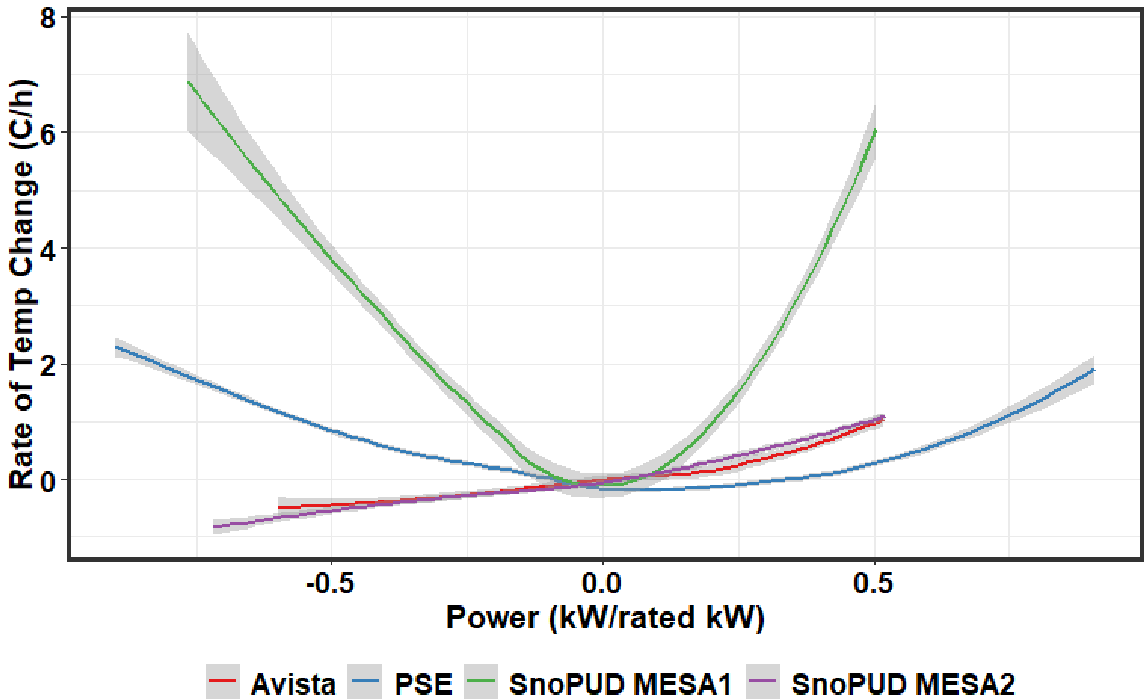

Figure 8.1. Change in Temperature as Function of Power for All Utilities

Table 8.2. Comparison of Metrics that Determine Rate of Temperature Rise for a Fixed Percent of Rated Power Across all Technologies

	E/P (h)	kg/MWh[1]	kg/MW	Normalized kg/MW	Normalized mohms-MW	Normalized mohms-MW/ Normalized kg/W	(P/E)* Normalized Resistance
MESA1	0.5	11,111	5,556	1	20	20.0	40.0
PSE	2.2	11,111	24,444	4.4	4	0.9	1.8
Avista	4	50,000	200,000	36	110	3.1	27.5
MESA2	4	50,000	200,000	36	80	2.2	20.0

[1] 90 Wh/kg assumed for Li-ion BESS and 20 Wh/kg for FBESS.

9.0 System Availability

The FBESSs were available 50 to 55 percent of test days, while the PSE BESS was available for 75 percent of test days. The MESA1 BESS was available for only 25 percent of test days, mainly because it was also being used to provide demand response services to BPA. Removing the days lost due to demand response activities, MESA1 availability was 62 percent (Figure 9.1). Figure 9.2 shows the various categories of issues that contributed to the lost days. For FBESSs, DC battery-related issues dominated, followed by maintenance. Among Li-ion BESSs, scheduled maintenance was the main contributor for PSE; unknown reasons, grouped into the miscellaneous category, were the chief contributor to lost days at MESA1.

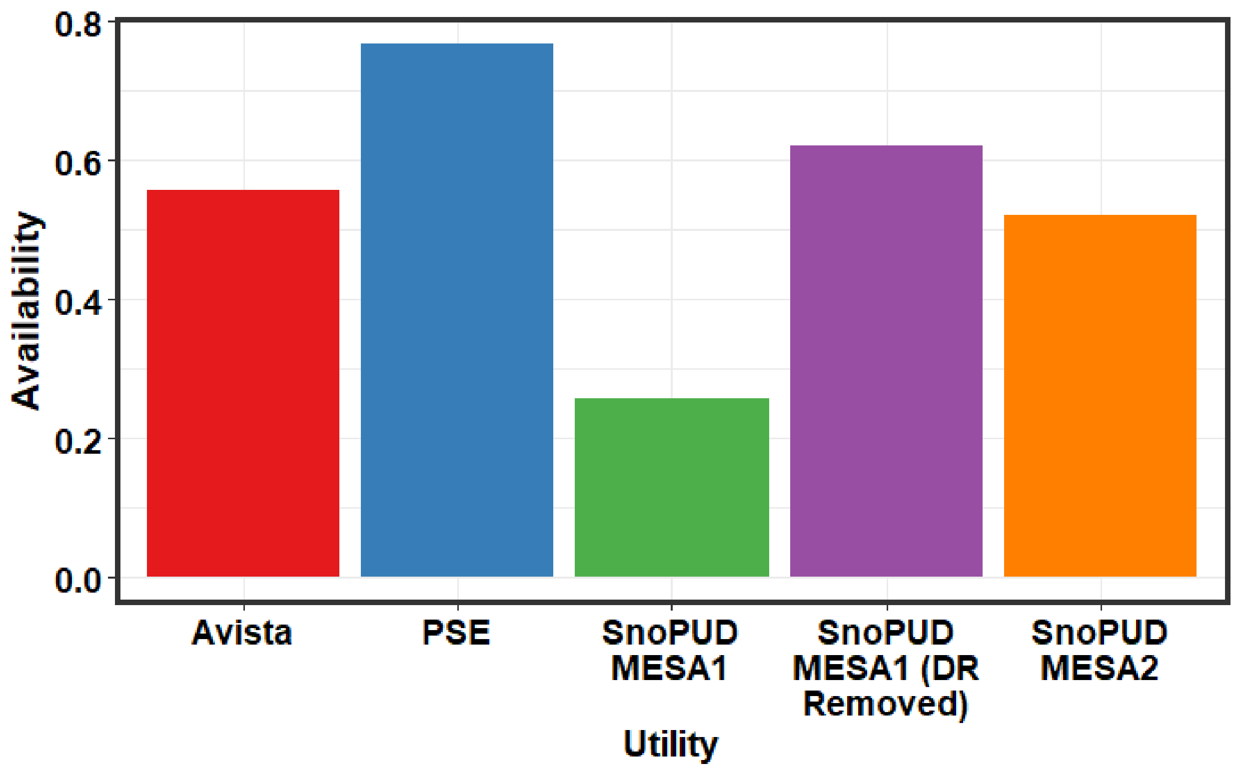

Figure 9.1. System Availability for Each BESS

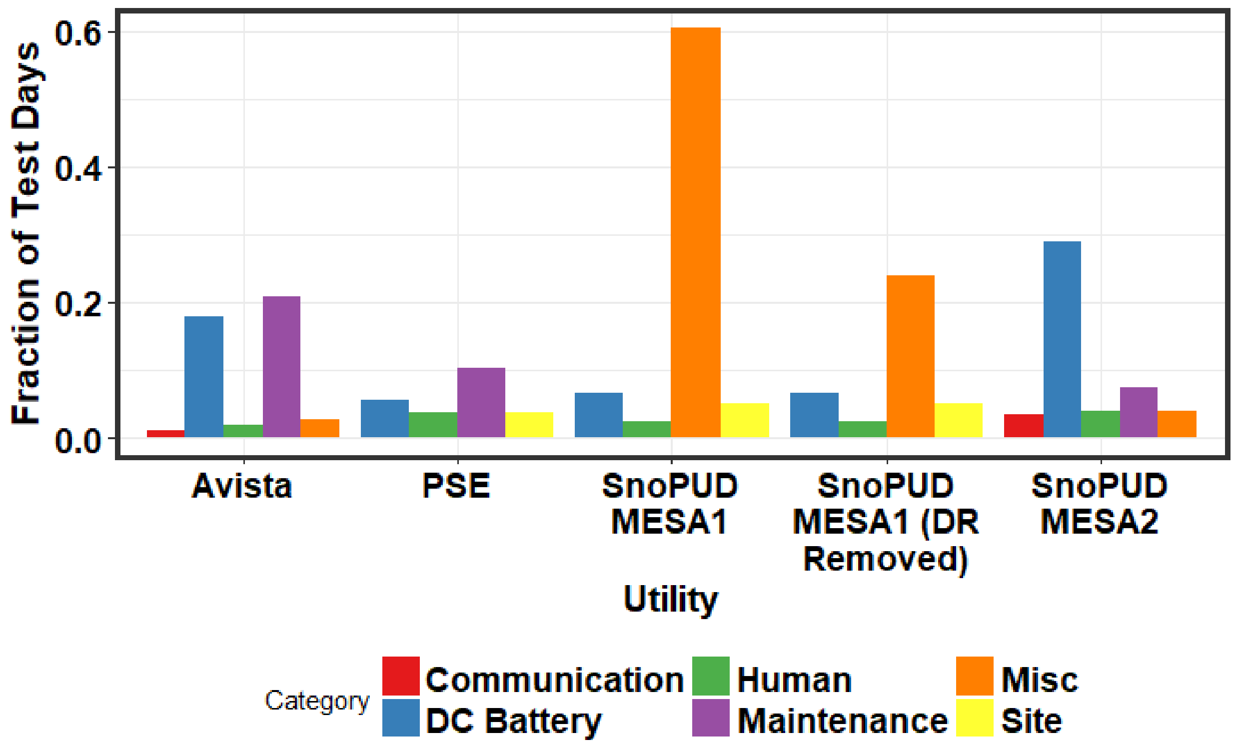

Figure 9.2. Contribution to Days Lost from Various Categories

10.0 Conclusions

The performance testing and analysis results support a conclusion that all technologies evaluated are technically feasible for performing the range of use cases demonstrated and planned; however, both FBESSs have ceased operation. The li-ion technologies do appear capable of performing over the 10-year (minimum) service life. However, the wide range of recorded key metrics could lead to significantly different outcomes in determining the economic viability of these respective technologies in specific use cases and projects. Figure 10.1 presents determined values for all performance metrics across all utilities. This enables the end user to select the appropriate technology for various grid services.

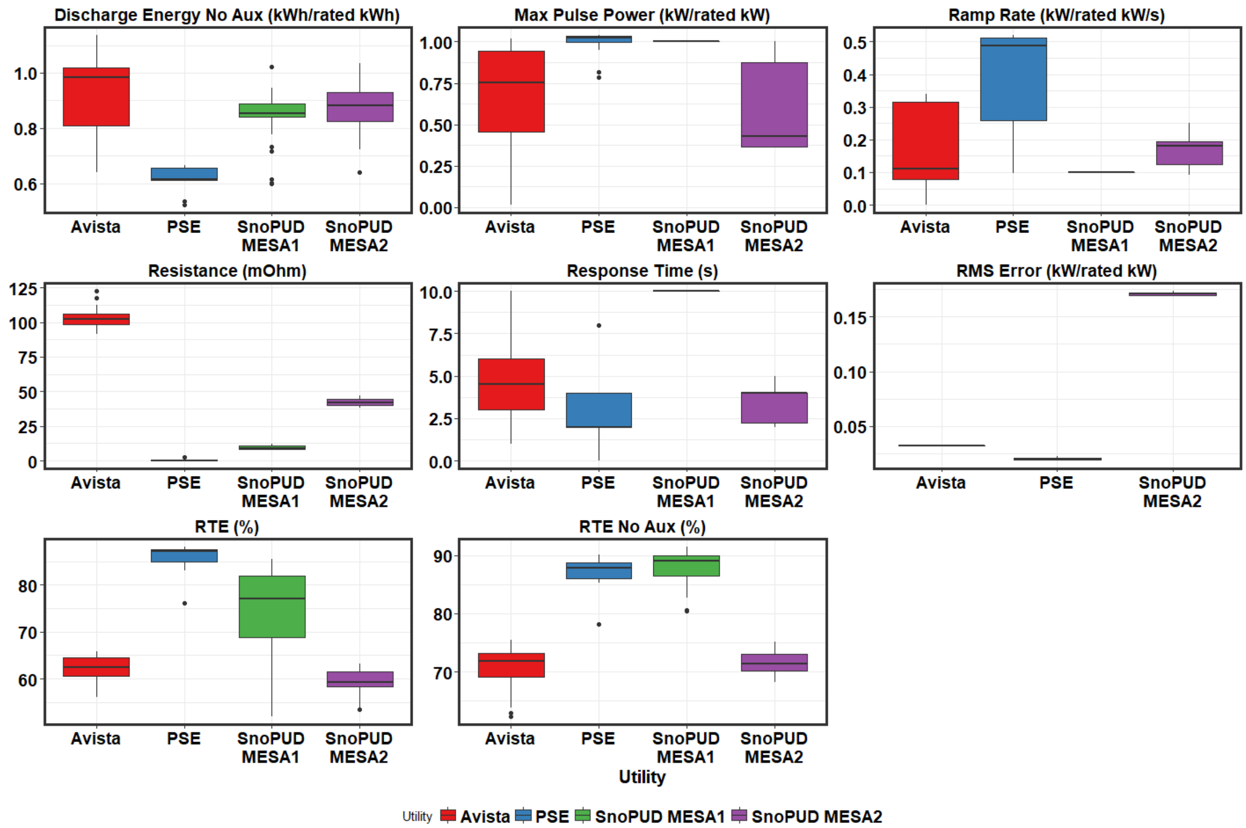

Figure 10.1. Performance of BESS for All Utilities

For example, there was a very wide range of measured RTE's from 57 to 90%. The sensitivity of RTE to economic viability is use case dependent; however, when RTE is an impactful economic variable for a specific project, this metric can be a differentiating factor when choosing between battery and PCS technology options. Further, for any use case to be economical, the availability factor needs to be high. Again, the results across the four systems varied widely, with availabilities ranging from 52 to 77%.

The use of the DOE-OE Test Protocol for the design of consistent testing, measurement, and post processing allowed for the comparison of a disparate set of technologies across a range of project deployment settings and use cases. The use of common 'open source' protocols and procedures allows for extending this analysis and comparing additional electrochemistries as they are developed and demonstrated in Washington State and the wider United States.

Key questions and outcomes of this study are discussed below.

1. What is the range of normalized energy during the reference performance capacity tests for all technologies?

   The DOD for the tested Li-ion BESSs was restricted to 72 to 85% of their operating ranges. This restricted the delivered energy to 63 to 85% of rated energy. There are no such restrictions with the FBESSs. Thus, the maximum discharge energy for FBESSs exceeded their rated energy in some cases when excluding auxiliary loads. Li-ion systems showed a low variance in energy delivered, with 50% of discharge cycles by the PSE BESS and SnoPUD MESA1 BESS staying within a 5% range of discharge energy per rated energy. By contrast, the FBESSs had a wider variance, with 50% of discharge cycles by the Avista FBESS and SnoPUD MESA2 FBESS falling within a 21% and 10% range, respectively (Figure 10.2).

   Most of the variance in the FBESS delivered energy without auxiliary loads can be explained by varying charge and discharge powers, with the two FBESS systems exhibiting an almost identical trend (Figure 10.2). By contrast, the amount of energy is almost flat with respect to discharge powers for the two Li-ion systems, with the SnoPUD MESA1 BESS delivering the least energy at the lowest discharge rates. This drop at low discharge rate is due to the temperature effect, with the battery running cold during low discharge resulting in less energy discharged.

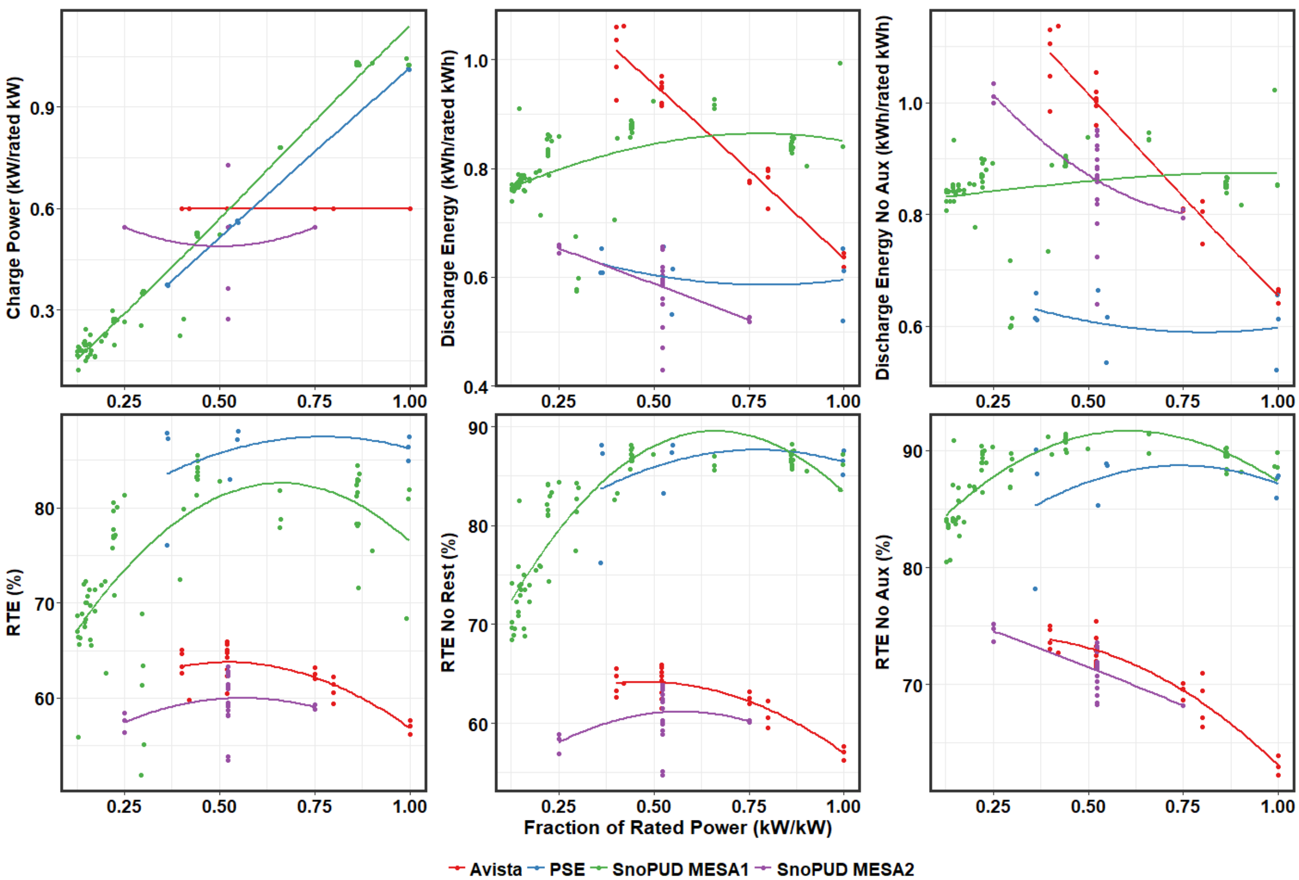

Figure 10.2. Performance of BESS for All Utilities during Reference Performance Capacity Tests

2. What is the RTE for each technology at rated power?

   The RTE for the PSE Li-ion BESS at 86% was much higher than the MESA1 Li-ion BESS at 75% due to higher auxiliary consumption of the latter associated with its high P/E ratio (Figure 10.3). The SnoPUD MESA1 BESS also had more variance, with the RTE ranging from 75.5 to 81.9% at max power. The PSE RTE ranged from 84.9 to 87.5%. The FBESS RTE at maximum power was very consistent, with a range of 56.2 to 57.1% for the Avista FBESS and 58.8 to 59.3% for the SnoPUD MESA2 FBESS. RTEs for the FBESSs were in the 55 to 60% range when discharged at 50% of rated power.

   The RTE for Li-ion BESSs was higher than FBESSs across all power levels, including and excluding auxiliary consumption.

   Excluding auxiliary consumption, the RTE for the MESA1 Li-ion BESS was highest in the 50% rated power to 100% rated power range, which corresponds to discharge in the 1C to 2C rate. The RTE for the PSE Li-ion BESS did not depend highly on the power levels investigated, which corresponded to the C/2 to C/6 range.

   The RTE for the arbitrage and system capacity use cases was low for MESA1 due to its low E/P ratio requiring it to be operated at low power levels. Only when it was operated at 0.4 times rated power (or 0.8C rate) does the RTE approach 80%. At higher power levels, the low E/P ratio restricts its operating duration, resulting in rest times dominating test duration. This was not observed for the other BESSs, which had E/P ratios > 2.2h.

   Operating the MESA1 Li-ion BESS at low power levels adversely affects its RTE due to its nearly 3x auxiliary consumption compared to the PSE BESS. Even when auxiliary losses are excluded, low power operation for MESA1 results in poorer performance related to lower temperature. However, it can be misleading to use the poorer performance as a criterion to avoid using low power levels or using the better performance at high power levels as a criterion to use high power levels because battery degradation is faster at high temperature. Considering degradation and performance, the optimal operating range for MESA1 appears to be 25 to 40 percent of rated power, where the BESS temperature does not reach temperature levels where degradation is expected to be significant.

   The PSE battery has a consistently high RTE for the power levels investigated, consistent with its 5x lower MW-normalized internal resistance and lower C rates compared to the MESA1 BESS. The auxiliary consumption as a percent of rated power is sufficiently low that it does not drag down RTE in the C/2 to C/6 rates of discharge.

   This work demonstrates the multiple factors that impact RTE – power, mode, temperature, SOC range of operation. While a flow battery performance model is useful in determining a priori what is to be expected, it needs to be adjusted any time the BESS system design is modified. For example, optimization of flow control would result in different performance for the same FBESS.

3. How important is auxiliary consumption?

   The RTE for the SnoPUD MESA1 BESS, with its high P/E ratio, dropped at 12% of rated power due to a high contribution from auxiliary consumption. The PSE BESS was not tested below 37% rated power; hence, the RTE drop at low power was not observed. Excluding auxiliary consumption, the RTE at low power was not much lower than peak RTE for MESA1. The peak in RTE corresponded with higher operating temperatures. For FBESSs, the RTE decreased linearly with increasing power when auxiliary consumption was excluded.

The average auxiliary powers and the standard deviations are presented in Figure 10.3, with the two FBESSs having comparable auxiliary powers of around 3% of rated power. There was a bigger jump between the two Li-ion BESSs, likely due to their difference in P/E ratios.

FBESS auxiliary consumption as fraction of rated power was 2.6 times the MESA1 BESS and seven times the rate measures for the PSE BESS. Hence, auxiliary losses alone limit the maximum RTE to 80% for FBESSs at charge-discharge power levels of 25% of rated power.

These auxiliary loads mean that even when the battery is not exchanging power with the grid, the SOC will drop since the auxiliary requirement is being met by the battery discharging—this phenomenon is essential to modeling BESS operation.

Losses during rest emphasize the need to keep the BESS in operation for other use cases instead of being idle, with the rest duration limited to lower values for BESSs with high auxiliary consumption and/or low E/P ratios.

The option to place the BESS in standby mode with potentially lower auxiliary consumption should be explored for all FBESSs or BESSs with long idle times. To this end, information on auxiliary consumption during standby mode should be made available.

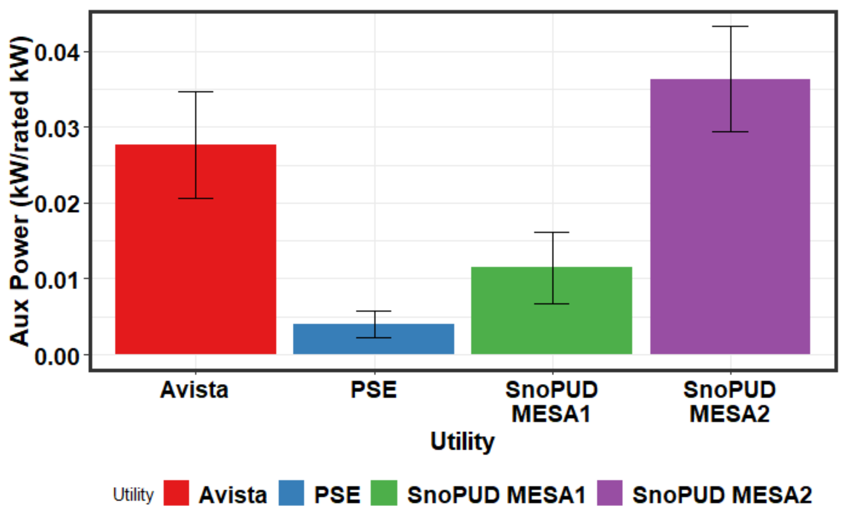

Figure 10.3. Average Auxiliary Consumption for All Utilities

4. How does SOC range of operation affect RTE?

   For Li-ion BESSs, RTE was not significantly affected by the SOC range of operation. For FBESSs, OCV decreases linearly with decreasing SOC so the RTE decreases as average SOC decreases. This was observed in use cases such as arbitrage or capacity, which had the unintuitive result of the RTE increasing with increasing power, contrary to reference performance test results. However, upon investigation it was found that the low power cases also had a wider SOC range with a lower SOC floor; this exerted downward pressure on the RTE.

   The discharge energy for Li-ion BESSs was in line with change in SOC. For the FBESS, the discharge energy per unit change in SOC was dependent on the SOC range of operation, with higher values at high SOCs.

   These results were expected, as the performance of the FBESS is very sensitive to the SOC range of operation. As a proxy for how performance varies with SOC, we can look at the dependence of maximum charge or discharge power attainable on the SOC. The maximum FBESS charge or discharge power is heavily dependent on the SOC (Figure 10.4), while performance is more constant across the SOC range for the Li-ion BESS systems.

5. How was BESS performance affected by operating conditions?

   The RTE was highly dependent on average power, SOC range, and rest duration. While RPTs were performed across a wide SOC range, use case testing, such as arbitrage, subjected the BESS to different SOC ranges. Therefore, a battery model was developed to predict performance across a wide operating range to optimize the battery duty cycle for testing purposes. For example, long rest periods and low operating power can be detrimental to RTE, as during rest the auxiliary power still needs to be operated despite power not being exchanged with the grid. This operation reduces the battery SOC with no associated benefit. Frequency regulation, which typically has a low average power, registered low RTEs.

   String balancing was an issue for the PSE BESS – hence the SOC range was limited to 10 to 82%. This shows the importance of having a good maintenance procedure to enable full use of the BESS capabilities.

   For FBESSs, increasing the string count from 2 to 4 adversely affected reliability.

6. Can the battery technologies attain rated power across the entire SOC range?

   As seen in Figure 10.4, Li-ion BESSs can consistently attain rated power during charge and discharge across the SOC range tested, while FBESS power varies greatly with the SOC range of operation. For the Avista FBESS, maximum discharge power is only possible for SOCs greater than 40%, with the MESA2 FBESS requiring an SOC as high as 70% to attain maximum discharge. The same effect happens during charge, with Avista and MESA2 FBESSs only being able to attain maximum charge rate at SOCs less than 60%. Typically, when the battery is at an SOC that is not able to return rated charge or discharge, the maximum charge or discharge rate possible varies linearly with SOC.

   The discharge ramp rate for FBESSs was stable at 35% rated power per second at SOC > 25%. The charge ramp rate was vendor-restricted to 20% of rated power at 20% SOC and decreased with increasing SOC to 10% of rated power per second. MESA2 did not attain maximum power during discharge at < 35% SOC and during charge at > 55% SOC due to string imbalance issues.

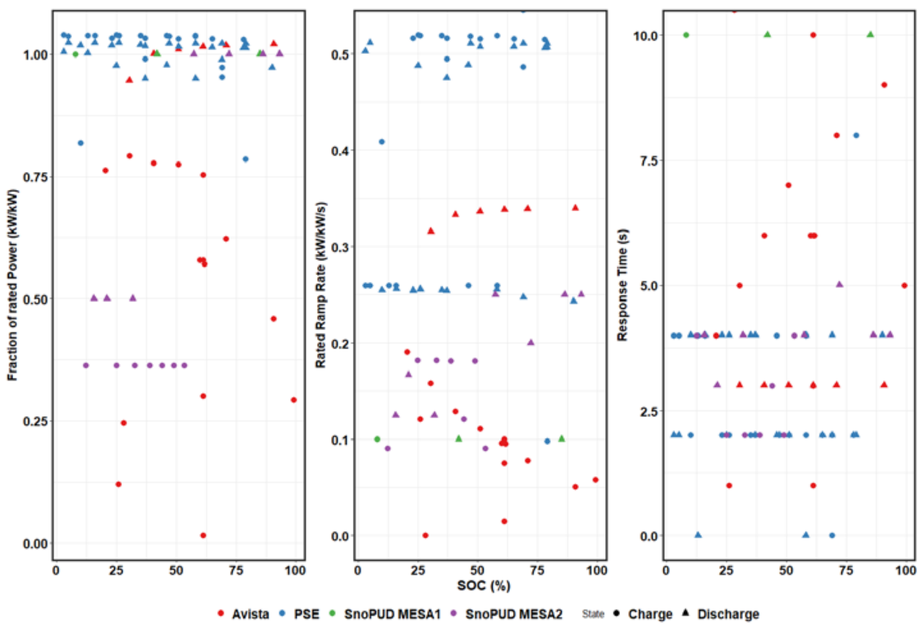

Figure 10.4. Response Test Data for All Utilities

7. What is the response time to maximum power for each technology?

   The response time was 2.5 to 5 seconds for all technologies when the SOC allowed for maximum power to be attained. We were unable to ascertain the response time for the SnoPUD MESA1 system because we had a data time resolution of 10 seconds.

   The ramp rate, based on limited analysis for the Li-ion BESSs, was a mirror image of the resistance, increasing when the resistance decreased and vice versa, while the response time increased with increasing resistance. The ramp rate for FBESSs depended heavily on the SOC of the system, with the charge ramp rate increasing with decreasing SOC, and the discharge ramp rate increasing with increasing SOC. The ramp rate and response time can be seen in Figure 10.4.

   The charge and discharge ramp rates for the PSE Li-ion BESS was either 25 or 50% of rated power per second. From the sparse data available for MESA1, the ramp rate was determined to be greater than 12.5% rated power per second.

   The FBESS charge ramp rate decreased steadily from 20% of rated power per second to 10% rated power per second as SOC increased above 20%. This can limit performance when high ramp rates are required in grid services such as photovoltaic smoothing.

   The Li-ion BESSs attain target power for charge and discharge during pulse testing, while FBESS maximum power tapers off at extreme SOCs, specifically as SOC increases during charge.

8. How did the batteries internal resistance compare?

   The internal resistance of the Avista and MESA2 FBESSs was 80 to 120 milliohms-MW, respectively, with the 2-String Avista FBESS showing marginally higher resistance. The Li-ion BESS internal resistance was an order of magnitude lower. This explains the stable discharge energy delivered across all power levels for the Li-ion BESSs.

   The product of P/E and normalized resistance is 20 times higher for MESA1 compared to PSE BESS. Hence as expected, the rate of temperature rise for MESA1 is higher for a fixed power. This product is ~ 24 for the FBESSs. The correct metric to use when comparing across technologies is the ratio of normalized resistance to mass per unit power. The higher this value, the greater the rate of change of temperature per unit of power. As expected, the MESA1 value for this metric is 20 times higher than PSE BESS and seven times higher than the FBESSs, in line with rate of temperature increase at various power levels.

9. How well did the batteries track a power signal?

   Both the Avista and PSE BESSs track the frequency regulation reference signal well, with an RMSE of 0.032 and 0.020 respectively. The numbers for MESA2 are not reliable, since signals could be sent only every 15 minutes.

   For volatile applications such as frequency regulation and load following, the average rated power is in the 0.4 to 0.08 times rated power range for the PSE BESS, while for the Avista FBESS it is in the 0.07 to 0.17 times rated power range. The RTE decreases steeply with decreasing average power in this range for both battery systems. This shows that while battery systems have good signal tracking, they do suffer from low RTE for these applications. Research into the design of PCSs that have high efficiency at low percent of rated power would address this issue.

10. What unique thermal management issues were identified?

    The FBESS reactions are net endothermic during charge, meaning that the temperature will drop during charge; Li-ion BESSs are net exothermic during charge and discharge. Since the FBESS did not have active heating, this necessitated multiple charge and discharge cycles during start-up in the winter to heat the FBESS. However, if heating is also present, this disadvantage turns into a net benefit, as the battery serves as a thermal management system due to cooling during charge followed by heating during discharge.

    For comparison across the same technology, the product of P/E and MW-normalized resistance was used as a proxy for the rate of rise of temperature per unit power. For comparison across technologies, the ratio of MW-normalized resistance to system mass per unit power was used as a proxy for the rate of rise of temperature per unit power. On both accounts, the MESA1 BESS had the highest numbers, in line with its highest rate of rise of temperature per unit power. Considering it is a high-power BESS, the battery choice does not appear to be in line with its end use.

    The rate of temperature change observed as a function of power is given in Figure 10.5. MESA1’s temperature changes much more rapidly than the other systems, presumably due to its lower thermal inertia per rated kW. This also means that the BESS’s temperature is very sensitive to how it is operating, which is why we unintuitively see higher efficiencies at higher power as the battery warms up and operates more efficiently.

    The thermal behavior for the Li-ion BESS and FBESS was different. There was a dominant cooling effect during charge for the FBESS, while the Li-ion BESS heated up during charge and discharge. The entropic term was endothermic during FBESS charge, while the reverse was true for the Li-ion BESS. While measurements are not available to calculate the entropic terms, the FBESS entropic term appears to have a greater influence than the Li-ion FBESS. Considering its MW-normalized resistance is 5 to 20 times greater than that measured for Li-ion BESSs, this appears to indicate the magnitude of the entropic contribution for FBESSs is much greater than that for Li-ion BESSs. These issues need to be considered while designing the FBESS or Li-Ion BESS thermal management system.

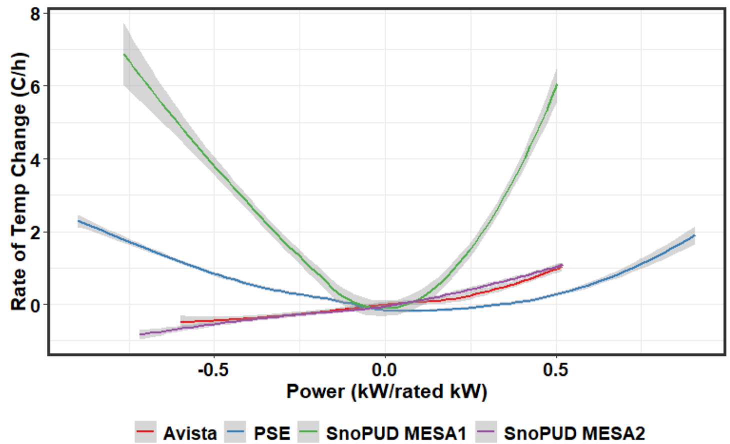

Figure 10.5. Rate of Temperature Change for All Utilities

11. What was the system availability?

    As seen in Figure 10.6, FBESSs were available 50 to 55% of test days, while Li-ion BESS availability was in the 62 to 75% range (with downtime for demand response participation removed). DC battery issues dominated FBESS unavailability, while DC battery and site-related issues dominated Li-ion BESS availability. Note that although at least one string was available for SnoPUD MESA2, all four strings were only available 28% of the time.

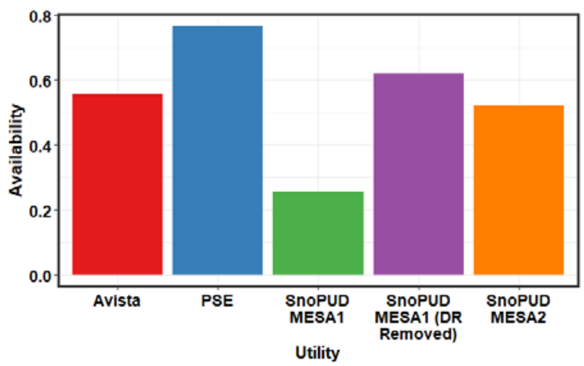

Figure 10.6. Availability for All Utilities

12. Was degradation observed for any technology?

    No, the test duration was not long enough to observe meaningful degradation (Figure 10.7). Any changes in discharge energy at different times are tiny compared to existing variance, with no clear downward trend. The exception is PSE, with what appears to be a downward trend in discharge energy. However, a corresponding increase in resistance is not observed; thus, we expect this decrease is due to battery balancing rather than degradation.

    The MESA2 battery did not complete the first cycle of tests. Hence, no conclusion can be made regarding its degradation over time. The Avista FBESS was stable over the two cycles of use case testing. This finding is in line with literature reports that FBESS performance does not degrade over time.

    The MESA1 BESS was stable after one cycle of use case testing. The PSE BESS performance decreased from baseline to post cycle 1 to post cycle 2. This was related to balancing-related issues, not due to degradation of the DC battery. For the PSE BESS, there was a slight conditioning affect at moderate SOC during ramp rate testing, while at low SOC during discharge and high SOC during charge, there was a slight degradation in performance after post cycle 1. This information is useful to ensure an appropriate operating envelop as the BESS ages.

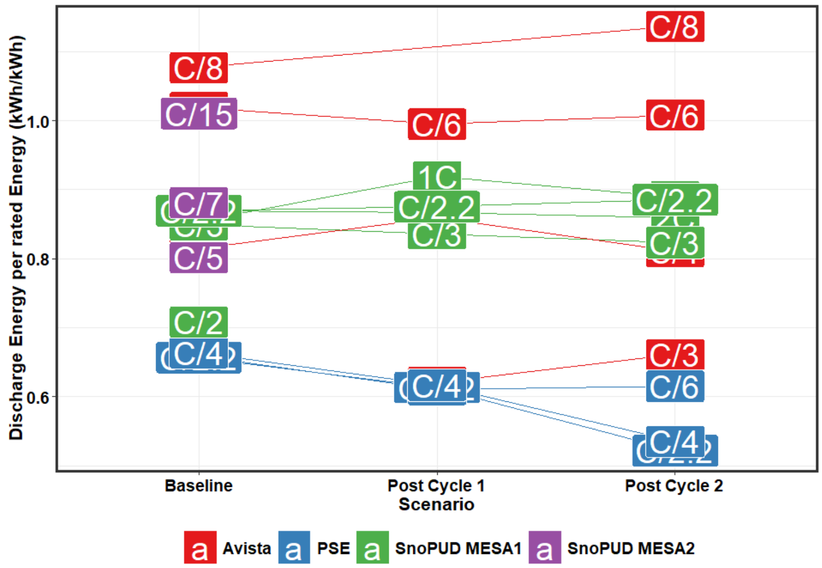

Figure 10.7. Discharge Energy for Each Round of Reference Performance Capacity Test

13. What was the overarching site controller issue that needed to be addressed?

    Commands to the FBESS are sent at the inverter level, while the FBESS response is tracked at the grid level. This leads to the FBESS providing less power than requested during discharge and absorbing more power during charge to power auxiliary loads. System tracking at the grid level for volatile signals is poor for the same reason.

    Communication-related delays need to be accounted for, especially for use cases such as frequency response and frequency regulation, where response time of the FBESS is important. For example, the PSE site had an ~5-second communication delay that was accounted for in signal processing.

11.0 References

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